

U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-297 873

**A Technical and Economic
Evaluation of the Project in
Baltimore, Maryland. Volume IV**

Systems Technology Corp, Xenia, OH

Prepared for

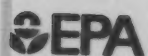
Environmental Protection Agency, Washington, DC Office of Solid Waste

Jun 79

United States
Environmental Protection
Agency

Office of Water
& Waste Management
Washington, DC 20460

SW 175C.4
June 1979



Solid Waste

PB 297873

A Technical and Economic Evaluation Of the Project In Baltimore, Maryland

Volume IV

REPRODUCED BY
**NATIONAL TECHNICAL
INFORMATION SERVICE**
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

BIBLIOGRAPHIC INFORMATION

PB-297 873

A Technical and Economic Evaluation of the Project in
Baltimore, Maryland. Volume IV.

Jun 79

PERFORMER: Systems Technology Corp., Xenia, OH.
Contract EPA-68-01-4359

SPONSOR: Environmental Protection Agency, Washington, DC.
Office of Solid Waste.
EPA/530/SW175C.4
Rept. for 1 Oct 75-30 Apr 78

See also Volume 3, PB-297 872.

This report is a complete technical, economic, and
environmental evaluation of the Landgard Demonstration Plant
at Baltimore, Maryland. It presents an introductory problem
analysis of most of the major innovations that proved
ineffective, caused serious shutdowns, and required redesign
or abandonment.

KEYWORDS: *Solid waste disposal, *Municipal wastes, *Waste
processing plants.

Available from the National Technical Information Service,
Springfield, Va. 22161

PRICE CODE: PC A05/MF A01

A TECHNICAL AND ECONOMIC EVALUATION OF THE
PROJECT IN BALTIMORE, MARYLAND

Volume IV

This report (SW175c) describes work performed
for the Office of Solid Waste under contract no. 68-01-4359
and is reproduced in four volumes as received from the contractor.
The findings should be attributed to the contractor
and not to the Office of Solid Waste.

U.S. ENVIRONMENTAL PROTECTION AGENCY

1979

j.a

This report was prepared by Systems Technology Corporation, Xenia, Ohio, under Contract No. 68-01-4359.

Publication does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of commercial products constitute endorsement by the U.S. Government.

An environmental protection publication (SW175c) in the solid waste management series.

PREFACE

This report is a complete technical, economic, and environmental evaluation of the Landgard® Demonstration Plant at Baltimore, Maryland. Because of its bulk and to serve a twofold purpose, the report is presented in four volumes: an executive summary, the report proper, an analysis of the problems, and the appendices. Intended particularly for resource recovery planners and administrators, the executive summary briefly and succinctly describes the Landgard® concept and Baltimore application for the state-of-the-art advancement in the processing of municipal mixed solid waste. In addition, it presents an introductory problem analysis of most of the major innovations that proved ineffective, caused serious shutdowns, and required redesign or abandonment. As the second, third, and fourth volumes are detailed in-depth accounts of the evaluation, they were prepared primarily for the designer. Of the four volumes, only the executive summary has been prepared for wide distribution in a paper copy format. The second, third, and fourth volumes are reproduced on microfiche, which is readily available through NTIS.

ABSTRACT

One of the first efforts in this country to demonstrate solid waste resource recovery technology was the Baltimore Landgard® project which was a joint venture between the City of Baltimore, the U.S. Environmental Protection Agency (EPA), the Maryland Environmental Service, and Monsanto EnviroChem. The Baltimore plant was designed and built by Monsanto EnviroChem to thermally process (pyrolyze) 907 Mg (1000 tons) per day of mixed municipal solid waste, convert it to energy (in the form of steam), and recover magnetic metals and glassy aggregate. Although the plant has never been fully operational in its original design configuration, considerable knowledge has been gained from it concerning resource recovery from municipal solid waste. The numerous equipment breakdowns and the inability of the plant to comply with air pollution standards accounted for the major difficulties encountered during the project. Major equipment problems were encountered with the storage and recovery unit, the refractory in the thermal processing vessels, the main induced-draft fan, the residue discharge drag conveyor, and the slag discharge screw conveyor. Despite the fact that the designer recommended converting the plant to a conventional incinerator, plant performance has been sufficiently encouraging to warrant continued investment and operation by the City of Baltimore. One of the primary reasons for this attitude by the City is that the rotary processing kiln has been demonstrated to be an excellent primary reaction vessel. Although the present plant is not environmentally acceptable because of high particulate emissions, this problem will be resolved by the installation of two electrostatic precipitators.

The thermal efficiency of the plant was determined to be approximately 56 percent for an average feed rate of 454 kg per minute (30 tph). The plant has a capital cost of approximately \$22 million, an annual operating and maintenance cost of \$3 million, and an annual steam revenue of \$1 million. The net operating cost, based on historical operating data, is \$64.10 per Mg (\$58.20 per ton) of refuse processed. However, if the annual throughput of 67,000 Mg (74,000 tons) could be substantially increased to 270,000 Mg (300,000 tons), operating cost could be reduced to \$7.80 per Mg (\$7.10 per ton) of refuse processed.

This report is submitted in fulfillment of Contract No. 68-01-4359 by Systems Technology Corporation (SYSTECH) under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from October 1, 1975 to April 30, 1978.

CONTENTS

Preface	i
Abstract	ii
Figures	iv
Tables	vi
List of Unit Conversions	vii
Acknowledgment	viii
1. Introduction	1
2. Refractory	3
Kiln Refractory	3
Gas Purifier Refractory	5
Duct Refractory	40
3. Slagging	43
Slag Hole Plugging	43
Boiler Tube Slagging	48
4. Conveyors	55
Storage Pit and Shredder Feed Conveyors	55
Screw Conveyors	56
Residue Quench Tank Drag Conveyor	57
5. Ram Feeders	59
Ram Jams	59
Snout Failure	60
Hydraulic System	61
6. Storage and Recovery Unit	63
7. Residue Separation Module	66
8. System Pressure Oscillations	68
9. Kiln Process Control	72
10. O ₂ /CO ₂ Analyzer System	74
11. Induced Draft Fan	77
12. Scrubber Erosion and Corrosion	80
Scrubber Pumps	80
Scrubber Lances and Nozzles	81
13. Summary	82

FIGURES

<u>Number</u>		<u>Page</u>
1	Board-mounted assembly of all slag-refractory block specimens tested for slag penetration	7
2	SEM photographs of Alusite-D block specimen tested at 1425°C	9
3	SEM photographs of Altex-85 block specimen tested at 1375°C	12
4	SEM photographs of Altex-85 block specimen tested at 1425°C	13
5	SEM photographs of DV-38 block specimen tested at 1375°C . . .	16
6	SEM photographs of DV-38 block specimen tested at 1425°C . . .	17
7	SEM photographs of Lofero-HM block specimen tested at 1375°C	21
8	SEM photographs of Lofero-HM block specimen tested at 1425°C	22
9	SEM photographs of Nucon-60 block specimen tested at 1375°C	25
10	SEM photograph of Nucon-60 block specimen tested at 1425°C	26
11	SEM photographs of Oxibak-H block specimen tested at 1375°C	29
12	SEM photographs of Oxibak-H block specimen tested at 1425°C	30
13	SEM photographs of Korundal-XD block specimen tested at 1375°C	34

FIGURES (contd)

<u>Number</u>		<u>Page</u>
14	SEM photograph of Refrax-50A block specimen tested at 1375°C	37
15	A plot of slag viscosity based upon temperature and chemical composition	45
16	Slag temperature characteristics for satisfactory slag tapping	46
17	Slag viscosity based upon chemical composition	47
18	Scanning electron microscope pictures of fly ash	52
19	Optical microscope pictures of fly ash	53
20	Data trace of sinusoidal pressure pulsation in the kiln . . .	68
21	Data trace of random frequency pressure oscillations	69
22	Data trace of random frequency pressure oscillations	69
23	Data trace of dangerous pressure oscillations	69
24	Data traces of pressure at various locations	71

TABLES

<u>Number</u>		<u>Page</u>
1	Typical Slag Composition	5
2	Alusite-D Slag Penetration Test at 1375°C	10
3	Alusite-D Slag Penetration Test at 1425°C	11
4	Altex-85 Slag Penetration Test at 1375°C	14
5	Altex-85 Slag Penetration Test at 1425°C	15
6	DV-38 Slag Penetration Test at 1375°C	18
7	DV-38 Slag Penetration Test at 1425°C	19
8	Lofero Slag Penetration Test at 1375°C	23
9	Lofero Slag Penetration Test at 1425°C	24
10	Nucon-60 Slag Penetration Test at 1375°C	27
11	Nucon-60 Slag Penetration Test at 1425°C	28
12	Oxibak-H Slag Penetration Test at 1375°C	31
13	Oxibak-H Slag Penetration Test at 1425°C	32
14	Korkundal-XD Slag Penetration Test at 1375°C	35
15	Korkundal-XD Slag Penetration Test at 1425°C	36
16	Refractory Chemical Composition	36
17	Refrax-50A Slag Penetration Test at 1375°C	38

LIST OF UNIT CONVERSIONS

DESCRIPTION	SI		ENGLISH EQUIVALENTS	
	UNIT	SYMBOL	UNIT	SYMBOL
LENGTH	meter	(m)	3.28 feet	(ft)
	centimeter	(cm)	0.394 inches	(in.)
	millimeter	(mm)	39.37 mils	
	micrometer	(μ m)	1.0 micron	
AREA	square meter	(m ²)	10.76 square feet	(ft ²)
VOLUME	cubic meter	(m ³)	35.31 cubic feet	(ft ³)
	liter		0.264 gallons	(gal)
MASS	kilogram	(kg)	2.20 pounds	(lbs)
	megagrams	(Mg)	1.10 tons	
PRESSURE	kilopascal	(kPa)	0.145	(lbs/in. ²)
TEMPERATURE	celsius	(C)	5 fahrenheit/9-17.8	(F)
	joule	(J)	9.48 $\times 10^{-4}$	(Btu)
DENSITY		(kg/m ³)	.0624	(lbs/ft ³)
ENERGY/MASS		(MJ/kg)	431	(Btu/lb)
MASS LOADING		(g/DSCM)	0.437	(gr/DSCF)
CONCENTRATION		(μ l/l)	1.0	(ppm)
POWER	kilowatt	(kw)	0.06	(MJ/min)

ACKNOWLEDGMENT

This evaluation program was performed under EPA Contract No. 68-01-4359, "Technical and Economic Evaluation of the EPA Demonstration Resource Recovery Project in Baltimore, Maryland."

The EPA Project Officer was Mr. David B. Sussman of the Office of Solid Waste, Washington, D.C.

Testing was carried out at the demonstration facility in Baltimore, Maryland with the cooperation of the City plant staff and the Monsanto on-site engineering staff. The contribution of both of these groups has been greatly appreciated. The contribution of Dr. H. G. Rigo and Richard Eckels, along with other staff members, is also acknowledged.

Systems Technology Corporation would like to express its gratitude to the above named individuals and all others associated with this evaluation.

SECTION 1

INTRODUCTION

This last volume of the four-volume report on the Baltimore Pyrolysis demonstration project documents the investigation of the problems encountered during demonstration start-up and operation. The investigation was limited to critical problems; that is, failures, malfunctions, or discrepancies which either directly or indirectly caused operation shutdown. The reason for this limitation was twofold: first, there were too many minor problems to evaluate; and second, plant reliability, that is, continual operation, was the prime criterion in evaluating the plant's performance.

The problem investigation consisted of describing modifications implemented to resolve problems, of analyzing the problems, and of offering solutions to the unresolved problems. In addition, each of the critical problems was classified under one of the following three categories: (1) unique to the Landgard process, (2) unique to the Baltimore facility, and (3) typical of solid waste processing in general. To distinguish these categories, the "Landgard process" was defined to include the specific process of pyrolysis or starved-air incineration with subsequent combustion of the product gas and the basic equipment items to perform the process; the "Baltimore facility" was defined to include the construction materials and practices, the operating procedures, and the module and component arrangements peculiar to the Baltimore plant; and "general solid waste processing" was defined to include the equipment and operations common to a number of solid waste processing plants.

Each of the following sections addresses the problems related to a particular type of equipment, operation, or phenomenon. For each item in each section, the problem investigation consists generally of three parts. As a general introduction to the problem, the first part explains why the failure led to a plant shutdown along with a history of the failure and the modifications implemented to resolve the problem. The second part analyzes the problem and proposes solutions and recommendations. Finally, the third part classifies the problem according to the foregoing three categories.

A final section summarizes the analyses and recommendations and reviews the component requirements as related to the total system. This relationship is critical since some of the downtime was due to the incompatibility of the components, processes, and operators. While no single design was necessarily incorrect for the component itself, some components were designed without due consideration of the total system. Moreover, some components were incorrectly

designed because of erroneous estimates of the operating environment and/or the process streams.

Since much of the information for the problem analysis was covered in Volume II, this volume summarizes that information to minimize repetition.

SECTION 2

REFRACTORY

The refractory lining the interiors of the kiln, crossover duct, gas purifier, and ductwork protects the structure metals from excessive heat. A refractory failure at any point along this protective surface is cause in itself to shut down the system. A refractory failure may also indirectly prompt a system shutdown since the refractory fragments can damage or jam the residue drag conveyor, the slag screw conveyors, or block the slag flow into the residue outlet of the gas purifier.

A shutdown for refractory repair considerably increases the operating costs per throughput ton since the placement and proper cure of new castable refractory generally requires several days.

KILN REFRACTORY

Before any waste was fired, some of the original kiln refractory spalled off. Shortly after refuse processing was started, substantial amounts of the kiln refractory in the feed end of the kiln had to be replaced because of severe damage. Monsanto attributed this failure to the thermal shock caused by cooling water leaking out of the damaged ram snouts. To solve this problem, the water to the snouts was turned off, and consequently, the snouts eventually had to be replaced. In addition, the refractory at both ends of the kiln fell out regularly until the shell was slotted at both ends to allow for the movement of the kiln shell resulting from thermal expansion and contraction. Also, the refractory in the area of the kiln flights and spikes had to be frequently reinstalled because of failures attributed to patching the refractory during initial placement. After the entire kiln was relined, the refractory remained intact during the rest of the demonstration period.

As evidenced by the refractory spalling before any refuse was fired and by the need to replace the first 8 meters of refractory in the feed end shortly after the start of the refuse processing, the original refractory was probably worked excessively and improperly cured. The installation contractor's willingness to make financial adjustments would support this conclusion. Normally, after castable refractory has been installed, the heat for the refractory curing should not be applied for at least 24 hours. Then for a unit with the size of the kiln, a low-fire heat should be applied for a week to ten days to gradually dry out the refractory lining. When heat is applied too rapidly, it generates steam which is frequently trapped and can only be released by an explosive force which spalls the refractory. The

steam is more likely to be entrapped when the surface has been worked excessively by troweling the surface very smooth. The resulting smooth surface is too dense for the moisture to escape.

The kiln design criteria called for constant operating gas temperatures at 650°C (1200°F) to prevent slagging and residue fusing into large balls. Since slagging and residue fusing both occurred, the actual operating temperatures are acknowledged to have exceeded design temperatures considerably. The high temperatures probably caused anchor failure with the consequent loss of large pieces of refractory at the fire end of the kiln. While the cold mechanical strength of castable refractory is sufficient to maintain structural integrity at temperatures up to about 1093°C (2000°F), it falls off rapidly above this temperature. With the refractory strength so reduced, the pounding of the large masses of fused residue rolling in the kiln could disintegrate the refractory.

Metal refractory anchors have definite temperature limits: 927°C (1700°F) for 304 stainless steel and 1038°C (1900°F) for 310 stainless steel. Above these limits, castable refractories have a tendency to spall to the depth of the anchor tips. If the higher than designed operating temperatures could have been anticipated, the anchors would not have been made of metal. The actual operating conditions with metal anchors left no margin for processing temperature control error.

The problem of supporting the refractory shell within a rotating vessel was aggravated by constructing the kiln with two metals: mild or carbon steel for the shell, and stainless steel "end rings" as discussed in Volume II of this report. Therefore, the refractory for the kiln shell and that for the kiln end sections should have had expansion joints to compensate for the differential between the carbon steel and stainless steel.

The refractory spalling was probably due to a combination of thermal shock spalling and structural spalling. Thermal shock spalling is caused by thermal cycling during shutdown and start-up or by temperature variations during operation. While spalling can occur at any temperature, the degree of spalling is a function of the severity of the temperature change.

Structural spalling is caused by impurities within the refractory. As the kiln pyrolysis gas passes in and out of the permeable refractory, iron impurities in the refractory frequently dissociate carbon from carbon dioxide and hydrocarbons, especially methane, in the gas. The carbon so released deposits in the outer layers of the refractory. This process is very active in the range of 540°C to 1100°C (1000°F to 2012°F). Then as the refractory cools, the imbedded carbon produces stresses that cause spalling. The extent and frequency of such spalling is a function of the quantity of iron impurities in the refractory.

While the failure of the original refractory is considered unique to the Baltimore plant since it was due primarily to improper refractory installation and curing, the spalling of the present refractory is considered unique to

the Landgard process since it has been due to the kiln processing conditions. Improved process stability should contribute substantially to minimizing this spalling.

GAS PURIFIER REFRACTORY

The refractory failure in the gas purifier was less dramatic than that in the kiln. Rather than falling out in large pieces as in the kiln, the refractory in the gas purifier diminished by the constant decrease of its thickness at a rate of about 1 mm (0.04 in.) an operational day. The only dramatic refractory failures in the gas purifier occurred in the baffle and orifice walls. As the refractory thickness decreased, the gas purifier was first water-cooled by spraying water on the outside shell and ultimately required rebricking. The original gas purifier is currently being replaced by a nonslagging afterburner which will likely minimize refractory failure by reducing both the operating temperature and gas velocity. The refractory problems in the gas purifier were due basically to the design specifications that did not anticipate the actual operating conditions. In particular, the slag composition and the vessel temperatures differed considerably from those in the design data.

The alumina-silica refractory originally installed in the gas purifier is typically used for acid steel slag. The slag in the gas purifier was similar to a coal slag but with slightly lower iron and higher alkali metal concentrations (Table 1).

TABLE 1. TYPICAL SLAG COMPOSITION

Constituent	U.S. Coal (Percent by Weight)	Gas Purifier (Percent by Weight)
SiO ₂	20-60	57
Al ₂ O ₃	10-35	18
Fe ₂ O ₃	5-35	4
TiO ₂	0.5-2.5	3
CaO	1-20	9
MgO	0.3-4	2
Na ₂ O	0.1-2.4	4
K ₂ O	0.3-3.5	1
SO ₃	0.1-1.2	<1
P ₂ O ₅	—	2

Slag-Refractory Interactions

As a service to the City of Baltimore in the attempt to resolve the gas purifier refractory problem, the Bethlehem Steel Corporation conducted penetration tests with the gas purifier slag and the following 10 refractories to determine which of these refractories would serve best for the gas purifier rebricking:

- ALUSITE D (Harbison-Walker Refractories)
- ALTEX 85 (General Refractories Company) (original refractory)
- DV-38 (A.P. Green Refractories Co.)
- LOFERO HM (Kaiser Refractories)
- NUCON 60 (Harbison-Walker Refractories)
- OXIBAK H (Harbison-Walker Refractories)
- KORUNDAL XD (Harbison-Walker Refractories)
- REFRAX 50A (Carborundum Refractory Division)
- HARBIDE (Harbison-Walker Refractories)
- REFRAX 20 (Carborundum Refractory Division)

The test specimens were prepared as follows: For each of the 10 refractories, a hole or "cup" was bored into each of two blocks and the two holes were each loaded with a black gas purifier slag. Next, one block of each pair was heated in a furnace to 1375°C (2500°F), and the other block of the pair was heated to 1425°C (2600°F). Then the blocks were each cut in half through the cup axis to yield the specimens which were mounted on a board, as shown in Figure 1. Next, SYSTECH used the scanning electron microscopy (SEM) technique to collect two types of data for the assessment of the slag penetration into, and the slag attack on, the refractory.

One data type consisted of two differently magnified SEM photographs of each block specimen. The center point sighting for each photograph was at the midpoint of the bottom slag-refractory interface. Of the two SEM photographs for each block specimen, one is a 10× magnification, and the other is a 25× magnification. Also, for each block specimen, the second data type consisted of relative constituent percentages at each of several discrete points along the line perpendicular to the slag-refractory interface.

In the following side-by-side presentations of the magnified SEM photographs of each specimen block, the 10× magnification is at the left and the 25× magnification is at the right. The lines on each side of the individual photographs indicate the reaction zone at the slag-refractory interface where the slag and refractory are above and below the interface, respectively. In the 25× magnification, the light dots aligned vertically to the interface are the SEM probe points for the relative constituent percentage measurements. These points were numbered consecutively from the lowermost to the uppermost to denote their relative locations.

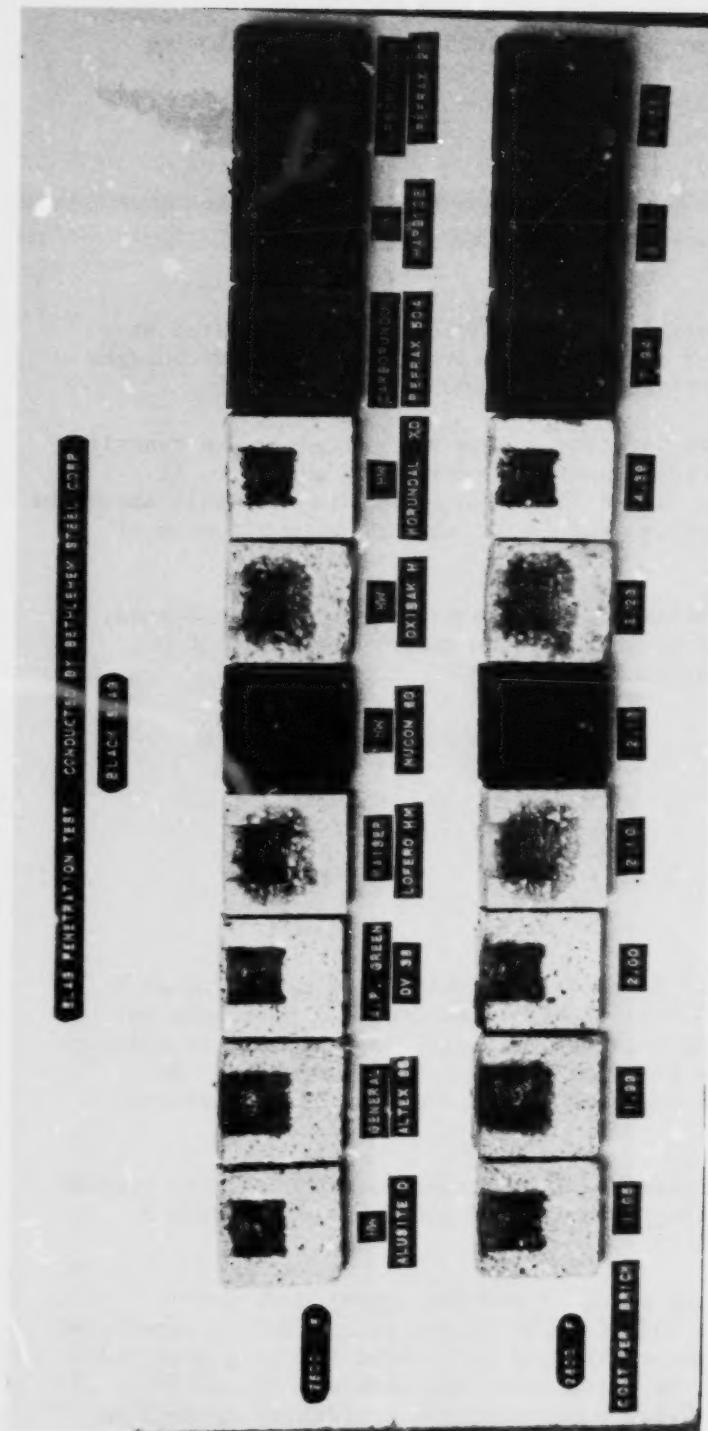


Figure 1. Board-mounted assembly of all slag-refractory block specimens tested for slag penetration.

Alusite D (Harbison-Walker Refractories), a fairly high alumina refractory which showed some evidence of phosphate bonding in the test specimen, has a maximum service temperature of 1650°C (1800°F) and the following chemical composition:

Al ₂ O ₃	71.8%
SiO ₂	22.9%
Fe ₂ O ₃	1.5%
MgO	0.2%
Lime	0.2%
Alkalies	0.5%

Figure 2 shows the SEM photographs of the block specimen tested at 1425°C (2600°F). Tables 2 and 3 list the relative constituent percentages for the tests at 1375°C (2500°F) and 1425°C (2600°F), respectively.

At 1375°C (2500°F) the slag penetration was very slight. The reaction interface is sharp with no degradation of the refractory surface. At 1425°C (2600°F) the penetration ranged from 1 to 3 mm. The cup wall above the slag pool was wetted. The reaction zone is 0.5 mm wide with evidence of SiO₂ attack.

Altex-85 (General Refractories Co.) is a phosphate-bonded, unburned, high-alumina refractory with an optimal service temperature of 1750°C (3200°F) and the following chemical composition:

Al ₂ O ₃	84.8%
SiO ₂	5.8%
TiO ₂	2.8%
Fe ₂ O ₃	2.0%
CaO	0.2%
MgO	0.4%
P ₂ O ₅	2.6%
Alkalies	0.2%

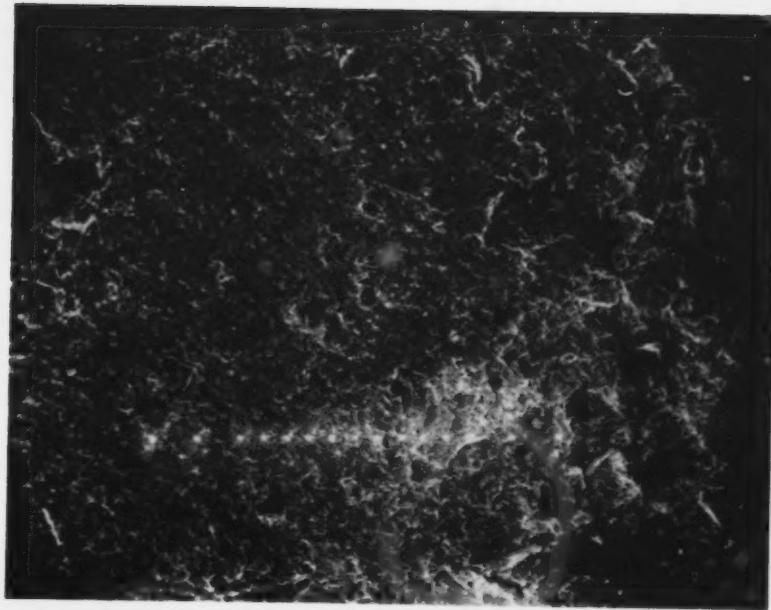
The SEM photographs (Figure 3 and 4) and constituent data (Tables 4 and 5) show that at 1375°C (2500°F) the slag dissolved 1.5 mm of the cup wall and penetrated 1 mm farther into the remaining wall. There is evidence of strong attack on SiO₂ in the reaction zone which is 1 mm wide. At 1425°C (2600°F) the results are the same except that the slag penetrated deeper, to approximately 3 mm.

DV-38 (A. P. Green Refractories Co.) is a phosphate-bonded, dry-pressed, high-alumina refractory containing a nominal 85 percent alumina with a fusion temperature of 1875°C (3425°F).

The SEM photographs (Figures 5 and 6) and the constituent data (Tables 6 and 7) reveal that at 1375°C (2500°F) the slag slightly penetrated the refractory. At this temperature the cup wall above the slag pool was wetted. The reaction interface is quite sharp but evidences some SiO₂ attack. At 1425°C (2600°F) the slag penetrated the refractory up to 1 mm



(10X)



(25X)

Figure 2. SEM photographs of Alusite-D block specimen tests at 1425°C.

TABLE 2. ALUSITE-D SLAG PENETRATION TEST AT 1375°C

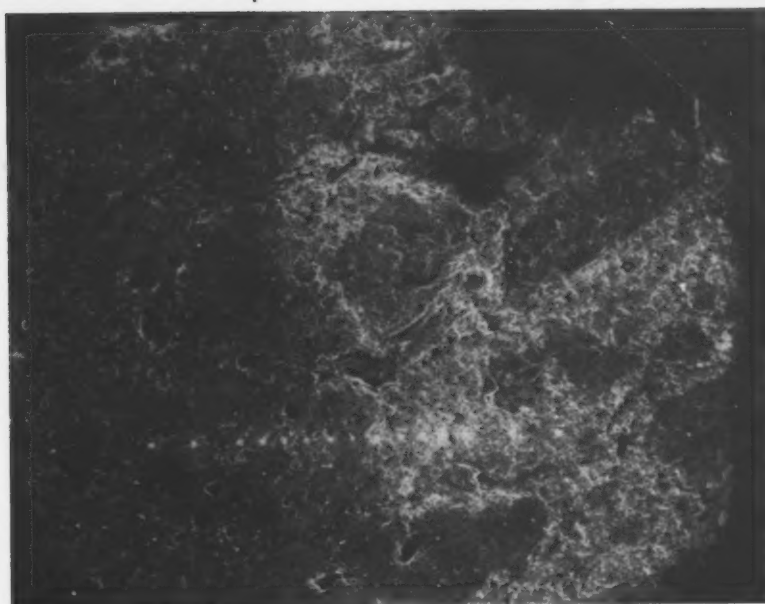
Location	Al	Si	Constituent (%)		K	Fe
			Ti	Ca		
3	22.08	48.05	1.30	27.27	1.30	----
4	22.84	48.35	2.06	23.66	2.06	1.03
5*	15.79	38.25	1.75	36.84	1.75	0.35
6†	21.26	52.68	4.07	21.63	4.07	0.92
7	24.95	51.90	1.00	21.96	----	0.20
8	77.10	20.61	2.29	-----	----	----
9	61.73	35.71	2.55	-----	----	----
10	-----	-----	----	-----	----	----
11	75.00	25.00	----	-----	----	----
12	50.37	49.62	----	-----	----	----
13	56.89	41.32	1.80	-----	----	----
14	48.00	52.00	----	-----	----	----

*S - 5.26

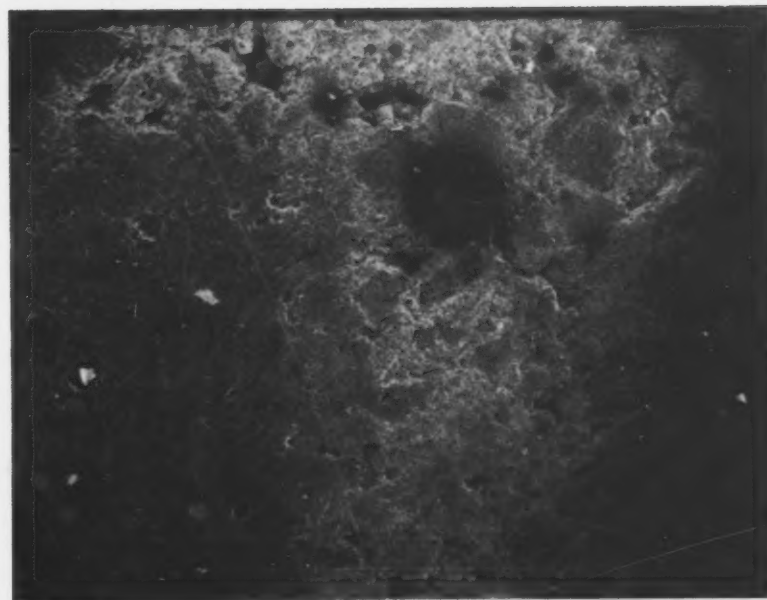
†P - 0.92

TABLE 3. ALUSITE-D SLAG PENETRATION TEST AT 1425°C

Location	Al	Si	Constituent (%)		
			Ti	Ca	Fe
1	27.07	49.62	1.50	22.56	----
2	28.25	53.11	1.13	16.95	----
3	29.09	38.18	----	30.91	----
4	75.68	18.02	1.80	3.60	----
5	27.03	40.54	2.70	29.73	----
6	-----	-----	----	-----	----
7	50.00	50.00	----	-----	----
8	51.81	43.37	3.61	-----	----
9	55.38	40.00	3.08	-----	----
10	77.06	21.10	0.92	-----	----
11	60.13	36.60	3.27	-----	----
12	55.33	37.33	3.33	4.00	----
13	69.72	25.69	4.59	-----	----
14	69.72	22.64	7.55	-----	1.89
15	68.18	22.72	5.30	-----	3.79

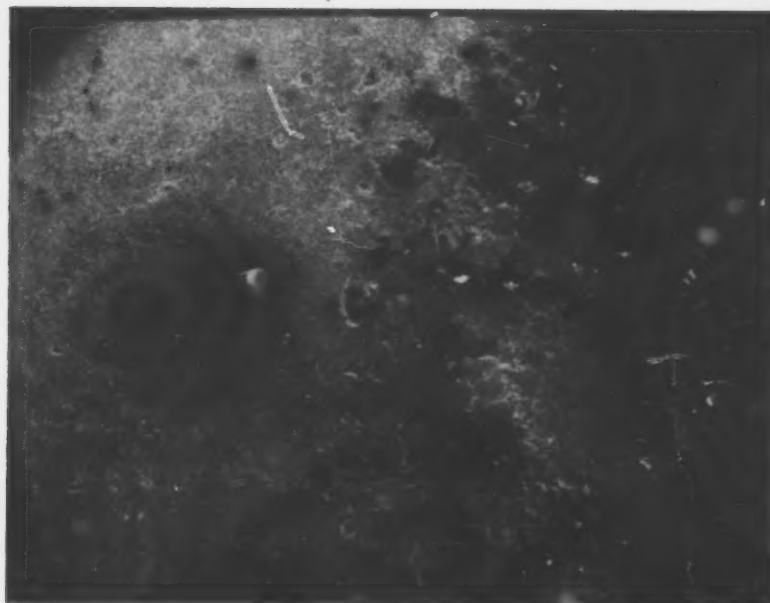


(25X)

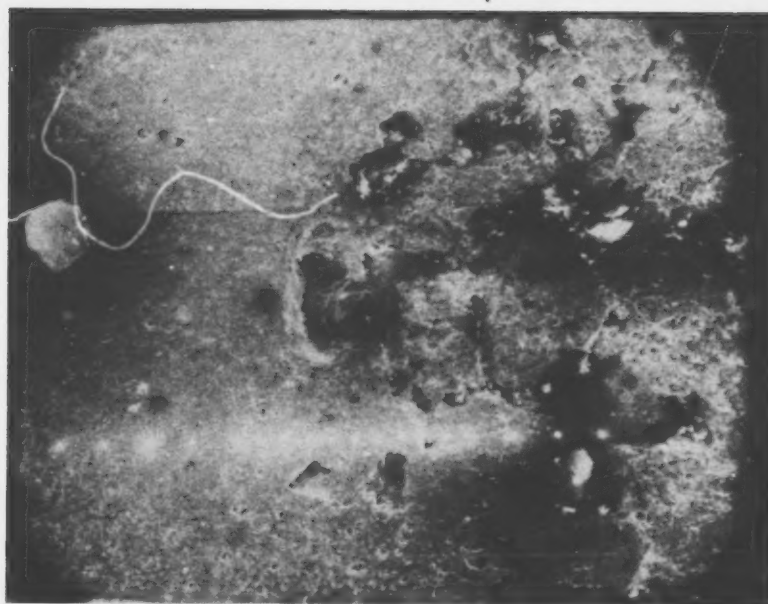


(10X)

Figure 3. SEM photographs of Altex-85 block specimen tested at 1375°C.



(10X)



(25X)

Figure 4. SEM photographs of Altex-85 block specimen tested at 1425°C.

TABLE 4. ALTEX-85 SLAG PENETRATION TEST AT 1375°C

Location	Al	Si	Constituent (%)		Fe	P
			Ca	Ti		
1	78.00	0.40	0.40	1.00	13.00	----
2	28.39	40.55	24.33	3.65	3.08	----
3	87.67	5.48	3.77	2.05	1.03	----
4	90.71	3.83	2.40	1.97	1.09	----
5*	46.03	34.13	7.94	5.56	3.17	0.79
6	81.82	9.09	4.55	2.27	2.27	----
7	83.10	8.10	2.11	4.23	1.06	1.41
8	87.50	5.21	-----	6.25	1.04	----
9	-----	-----	-----	-----	-----	----
10	68.09	23.83	0.85	2.13	1.70	3.40
11	75.96	17.80	-----	1.78	0.89	3.56
12	-----	-----	-----	-----	-----	----
13	57.14	34.29	2.86	2.86	1.90	0.95
14	70.18	3.51	-----	8.77	17.54	----
15	95.08	-----	-----	4.10	0.82	----

*K - 2.38

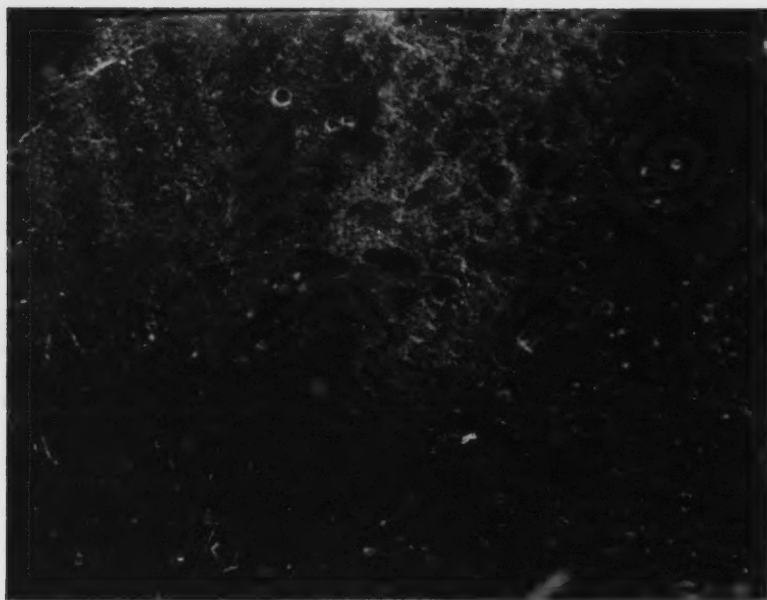
TABLE 5. ALTEX-85 SLAG PENETRATION TEST AT 1425°C

Location	Al	Si	Constituent (%)		Fe
			Ca	Ti	
1	23.91	41.30	26.80	5.80	2.17
2	22.86	32.38	32.38	8.57	3.81
3*	-----	-----	-----	-----	-----
4	97.17	1.77	1.06	-----	-----
5	99.32	-----	-----	0.34	0.34
6	-----	-----	-----	-----	-----
7†	21.88	12.50	-----	4.69	-----
8	90.11	6.59	-----	-----	3.30
9	81.15	14.14	-----	4.71	-----
10§	90.28	-----	-----	5.26	2.43
11	-----	-----	-----	-----	-----
12	-----	-----	-----	-----	-----
13	-----	-----	-----	-----	-----
14	79.36	18.35	-----	1.38	0.92
15	-----	-----	-----	-----	-----

* Ag - 1.0

† S - 17.97, Cl - 35.94, K - 6.25, Cu - 0.78

§ P - 2.02

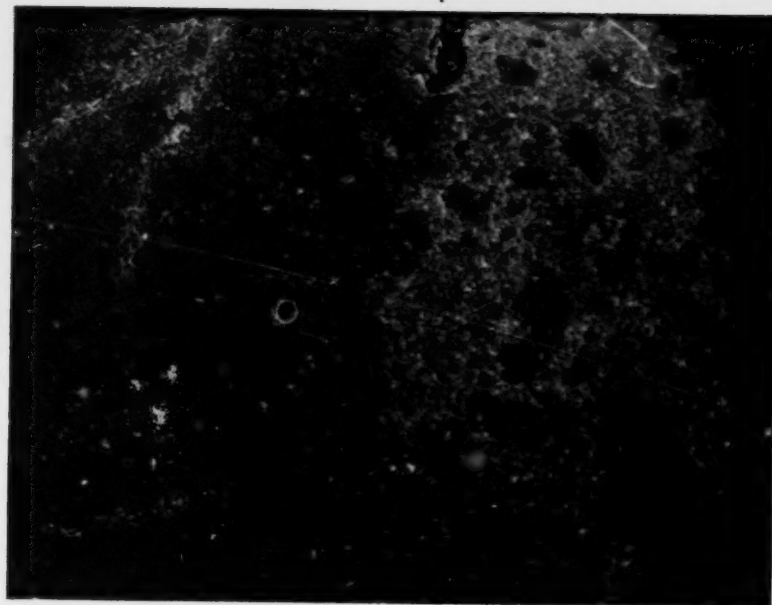


(10X)

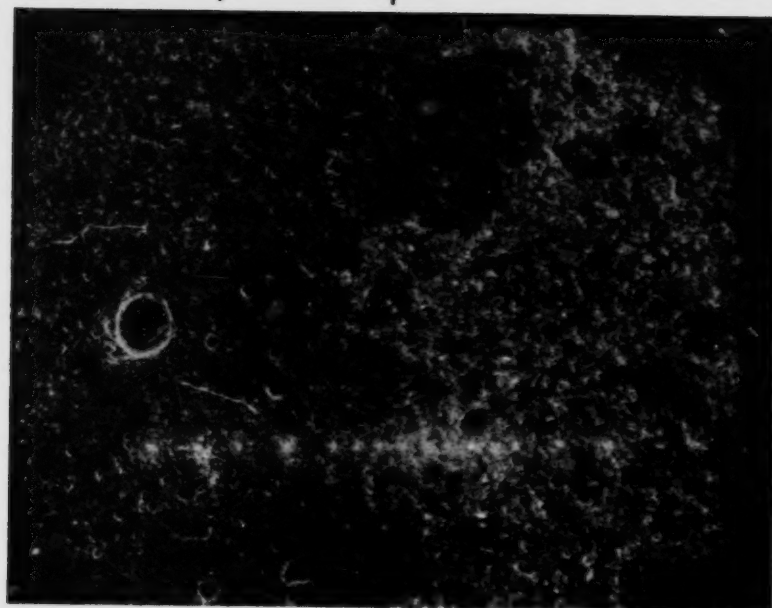


(25X)

Figure 5. SEM photographs of DV-38 block specimen tested at 1375°C.



(10X)



(25X)

Figure 6. SEM photographs of DV-38 block specimen tested at 1425°C.

TABLE 6. DV-38 SLAG PENETRATION TEST AT 1375°C

Location	Al	Si	Constituent (%)		Fe	P
			Ca	Ti		
1	79.25	-----	9.43	7.55	3.77	----
2*	67.69	20.51	3.59	2.56	0.51	3.08
3†	58.85	15.10	1.56	1.04	0.52	7.29
4‡	46.98	24.16	1.34	3.36	0.67	6.04
5	86.67	5.56	----	22.22	----	5.56
6	94.12	1.31	----	1.96	----	2.61
7	1.00	-----	----	-----	----	----
8	76.19	11.11	----	3.17	----	9.52
9§	54.68	35.97	----	2.16	0.72	2.88
10	84.91	4.72	----	3.30	2.36	4.72
11	-----	-----	----	-----	----	----
12	78.09	4.92	----	4.92	1.64	9.84
13	80.00	10.59	----	2.35	----	7.06

* K - 2.05

† F - 15.63

‡ K - 2.01, F - 15.44

§ K - 3.60

TABLE 7. DV-38 SLAG PENETRATION TEST AT 1425°C

Location	Al	Si	Constituent (%)		Fe	P
			Ca	Ti		
1	66.00	14.00	4.00	6.00	----	10.00
2	80.77	-----	----	5.77	----	13.46
3	83.95	12.35	----	2.50	1.23	-----
4	88.52	-----	----	11.48	----	-----
5	-----	-----	----	-----	----	-----
6	82.61	-----	----	4.35	----	13.04
7	90.20	-----	----	0.98	----	8.82
8	79.31	17.24	----	3.45	----	-----
9	60.00	30.00	----	10.00	----	-----
10	-----	-----	----	-----	----	-----
11	-----	-----	----	-----	----	-----
12	81.72	6.45	----	3.23	----	8.60
13	98.22	-----	----	1.13	1.61	-----
14	68.13	10.99	----	3.30	----	17.58

with the cup wall above the slag pool being wetted. The reaction interface is quite sharp at 1425°C (2600°F) but the attack was worse than that at the lower temperature.

Lofero HM (Kaiser Refractories) is a hard-burned, high-magnesium refractory formed from priclase with the following chemical composition:

MgO	98.0%
SiO ₂	0.7%
CaO	0.6%
Fe ₂ O ₃	0.4%
Al ₂ O ₃	0.3%

The SEM photographs (Figures 7 and 8) and the constituent data (Tables 8 and 9) show that the refractory totally absorbed the slag to a depth of 1 cm with a resultant severe attack of the material matrix and no clearly defined reaction interface.

Nucon 60 (Harbison-Walker Refractories) is a high-magnesia refractory with the following chemical composition:

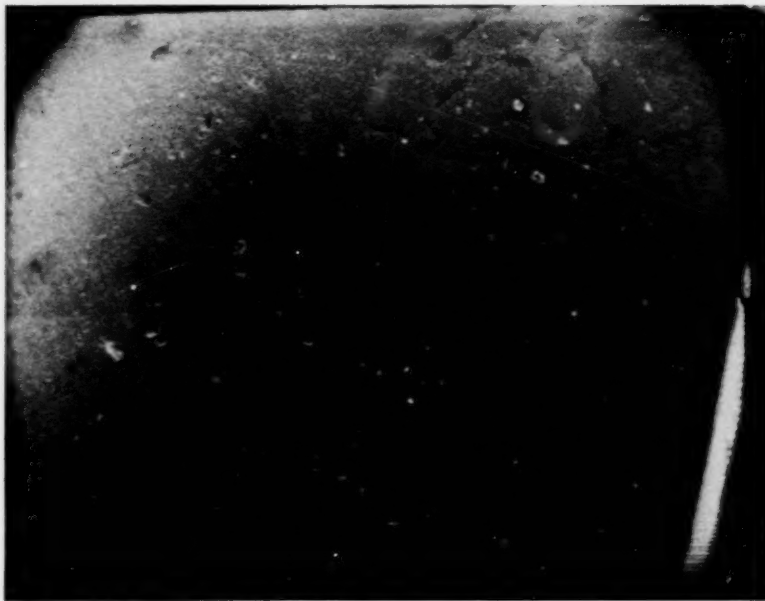
MgO	63.8%
SiO ₂	1.5%
Al ₂ O ₃	13.2%
Fe ₂ O	6.3%
Ca ₂ O ₃	14.5%
Lime	0.2%

As evidenced by the SEM photographs (Figures 9 and 10) and the constituent data (Tables 10 and 11) the slag was almost completely absorbed by the refractory at both temperatures to a depth of 1 cm with resultant moderate attack of the refractory surface and no clearly defined reaction interface.

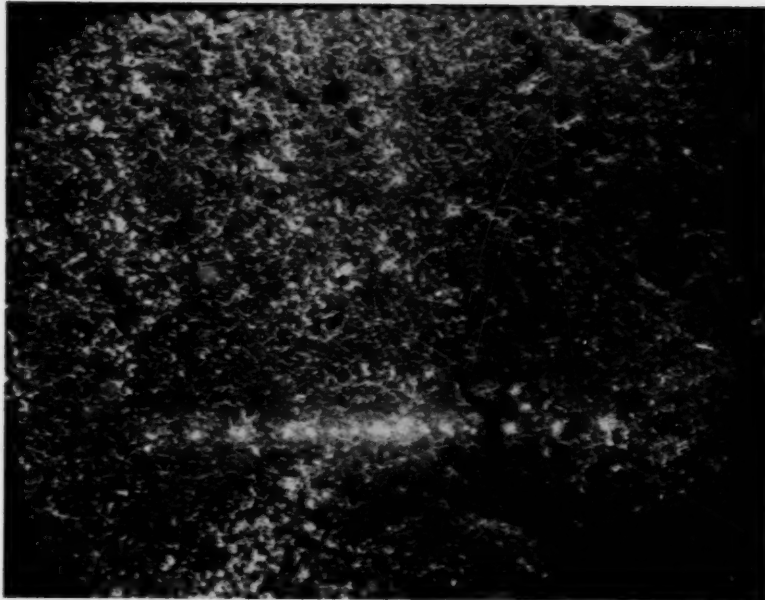
Oxibak H (Harbison-Walker Refractories) is a very high-magnesia refractory with course aggregate and the following chemical composition:

MgO	95.7%
SiO ₂	1.3%
Al ₂ O ₃	0.3%
Fe ₂ O ₃	0.3%
Lime	2.4%

The SEM photographs (Figures 11 and 12) and the constituent data (Tables 12 and 13) indicate that the slag was completely absorbed by the refractory at both temperatures to a depth of 1 cm. The slag attacked the refractory matrix so severely that refractory aggregate particles intermingle with the slag material in the reaction zone. Consequently, there is no clearly defined reaction interface.



(10X)

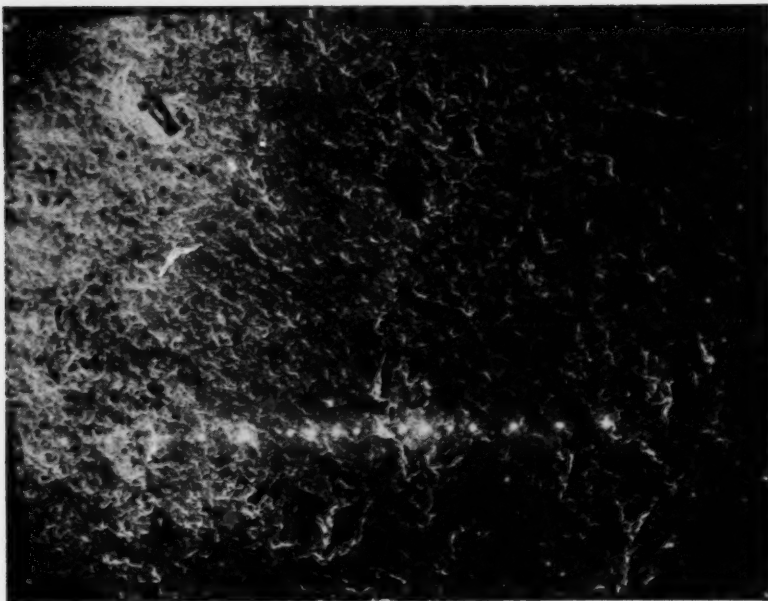


(25X)

Figure 7. SEM photographs of Lofero-HM block specimen tested at 1375°C.



(10X)



(25X)

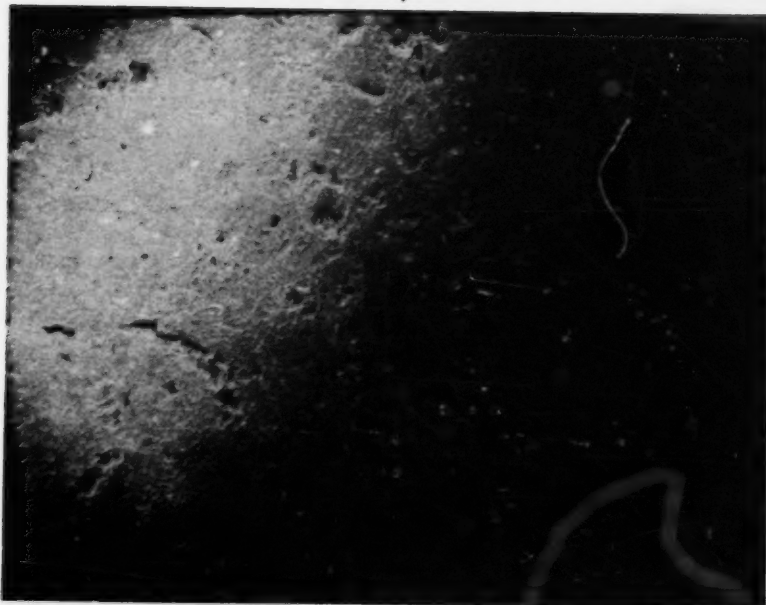
Figure 8. SEM photographs of Lofero-HM block specimen tested at 1425°C.

TABLE 8. LOFERO SLAG PENETRATION TEST AT 1375°C

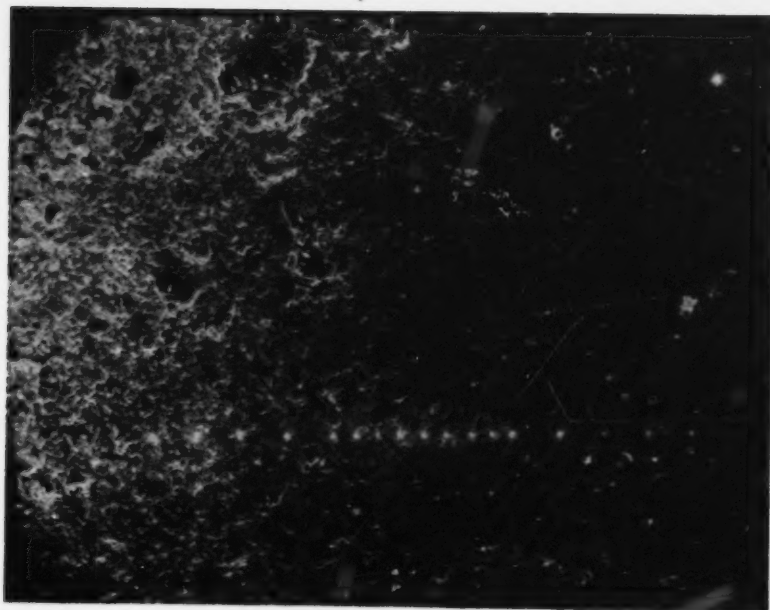
Location	Mg	Si	Ca	Al	Constituent (%)			
					Ti	Fe	S	K
1	40.88	43.80	14.33	-----	-----	-----	-----	-----
2	43.52	40.85	3.52	-----	0.70	-----	1.41	-----
3	59.34	30.77	3.30	-----	-----	1.10	3.30	2.20
4	56.10	31.71	6.10	-----	-----	-----	6.10	2.20
5	81.15	11.48	4.92	-----	-----	-----	2.46	-----
6	93.59	-----	-----	-----	-----	-----	6.41	-----
7	51.85	14.81	3.70	22.22	-----	7.41	-----	-----
8	90.00	-----	-----	-----	-----	-----	7.50	2.50
9	93.33	-----	-----	-----	-----	-----	5.00	1.67
10	69.35	-----	-----	-----	-----	-----	4.84	2.42
11	84.85	3.03	6.06	-----	-----	-----	6.06	
12	61.29	12.90	8.87	8.06	3.23	-----	1.61	4.03
13	71.43	5.71	11.43	4.29	-----	-----	7.14	-----
14	46.60	7.85	4.19	-----	-----	-----	2.62	1.05
15	90.57	1.89	3.77	-----	-----	-----	3.77	-----

TABLE 9. LOFERO SLAG PENETRATION TEST AT 1425°C

Location	Mg	Si	Ca	Constituent (%)			S	K
				Al	Ti	Fe		
1	50.54	46.24	3.22	-----	-----	-----	-----	-----
2	94.23	-----	-----	-----	-----	-----	5.77	-----
3	89.29	-----	-----	-----	-----	-----	10.71	-----
4	94.12	-----	-----	-----	-----	-----	5.88	-----
5	88.57	5.71	-----	-----	-----	-----	2.86	2.86
6	95.45	-----	-----	-----	-----	-----	4.55	-----
7	58.62	24.14	-----	17.24	-----	-----	-----	-----
8	50.00	16.67	16.67	-----	-----	-----	16.67	-----
9	97.09	-----	-----	-----	-----	-----	2.91	-----
10	27.78	38.89	33.33	-----	-----	-----	-----	-----
11	54.55	9.09	11.36	15.91	-----	-----	9.09	-----
12	46.43	41.07	8.93	-----	-----	-----	3.57	-----
13	43.48	-----	21.74	-----	-----	-----	26.09	8.70
14	24.19	19.35	32.26	-----	8.06	16.13	-----	-----
15	24.54	26.38	49.08	-----	-----	-----	-----	-----

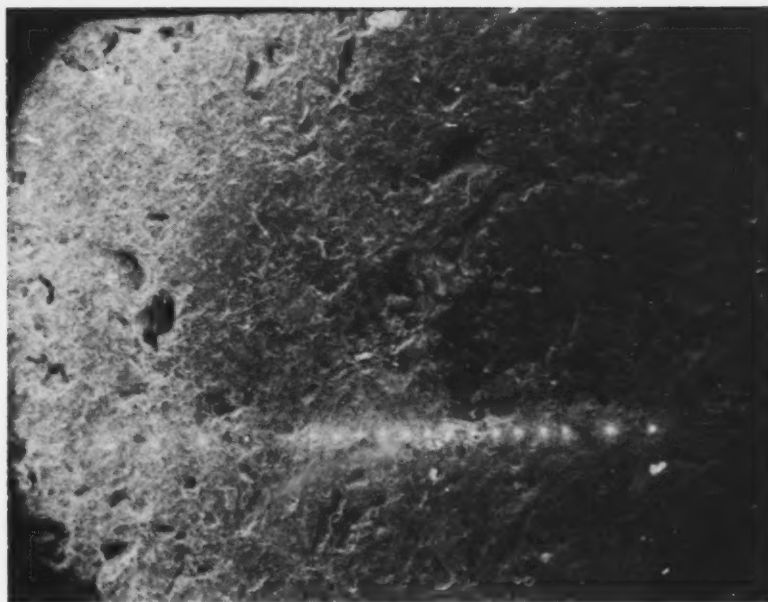


(10X)



(25X)

Figure 9. SEM photographs of Nucon-60 block specimen tested at 1375°C.



(25X)

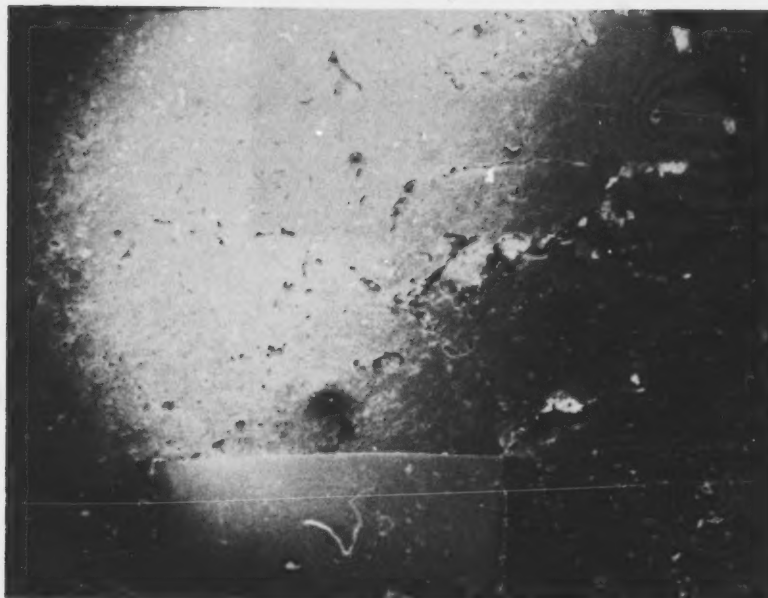
Figure 10. SEM photograph of Nucon-60 block specimen tested at 1425°C.

TABLE 10. NUCON-60 SLAG PENETRATION TEST AT 1375°C

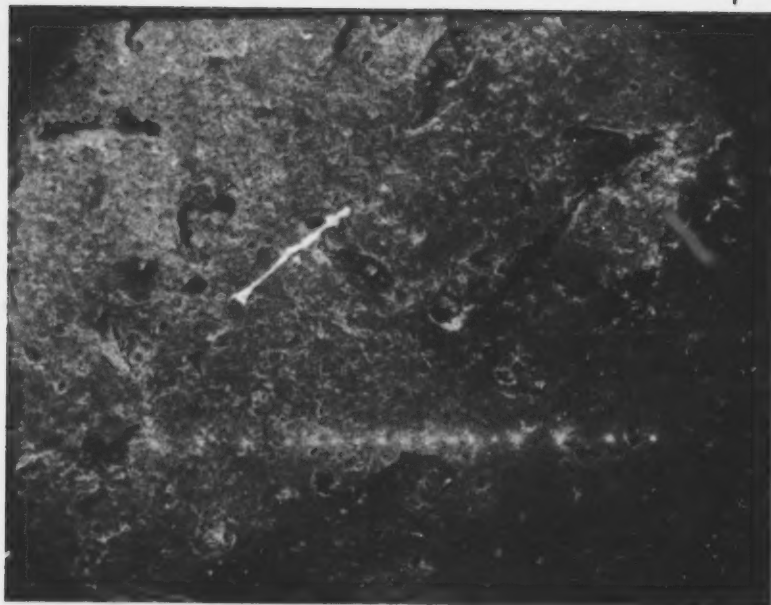
Location	Mg	Al	Si	Constituent (%)		Ca	S
				Cr	Fe		
1	22.92	-----	39.58	-----	-----	37.50	----
2	32.50	18.75	7.50	23.75	8.75	8.75	----
3	11.11	7.41	-----	59.26	22.22	-----	----
4	7.69	19.23	-----	61.54	5.77	-----	----
5	57.32	6.37	-----	22.29	10.83	-----	3.18
6	-----	-----	-----	40.54	59.46	-----	----
7	66.46	-----	3.16	15.82	11.39	3.16	----
8	51.72	-----	-----	24.14	24.14	-----	----
9	81.40	-----	-----	5.81	6.98	-----	----
10	87.12	-----	-----	7.58	5.30	-----	----
11	80.00	-----	-----	10.00	8.13	-----	1.88
12	46.58	-----	-----	34.25	19.18	-----	----
13	77.33	-----	-----	12.79	7.56	-----	2.33
14	75.68	-----	-----	13.51	10.81	-----	----
15	21.28	-----	-----	57.45	21.28	-----	----
16	23.91	10.87	26.09	10.51	4.71	23.91	----
17	76.92	-----	-----	10.00	6.92	-----	6.15

TABLE 11. NUCON-60 SLAG PENETRATION TESTS AT 1425°C

Location	Mg	Al	Si	Constituent (%)		Ca]	Ti
				Cr	Fe		
1	66.41	7.81	3.91	3.91	6.25	-----	----
2	15.60	31.91	2.84	46.10	3.55	-----	----
3	61.22	10.20	5.10	15.31	8.16	-----	----
4	64.10	-----	21.36	8.55	1.71	4.27	----
5	-----	-----	-----	-----	-----	-----	----
6	13.16	17.54	-----	62.28	7.02	-----	----
7	11.72	19.53	-----	62.50	6.25	-----	----
8	31.25	18.75	26.04	17.71	6.25	-----	----
9	25.96	21.15	16.35	24.04	12.50	-----	----
10	31.40	13.95	13.95	31.40	9.30	-----	----
11	51.28	-----	33.33	15.38	-----	-----	----
12	28.80	28.80	10.47	27.74	4.19	-----	----
13	37.37	-----	52.53	-----	-----	10.10	----
14	47.37	-----	42.11	-----	-----	10.53	----
15	64.62	-----	-----	23.08	12.31	-----	----
16	57.04	14.81	-----	22.22	5.93	-----	----
17	23.33	-----	46.67	-----	-----	26.67	3.33
18	50.00	-----	23.57	12.14	9.29	5.00	----

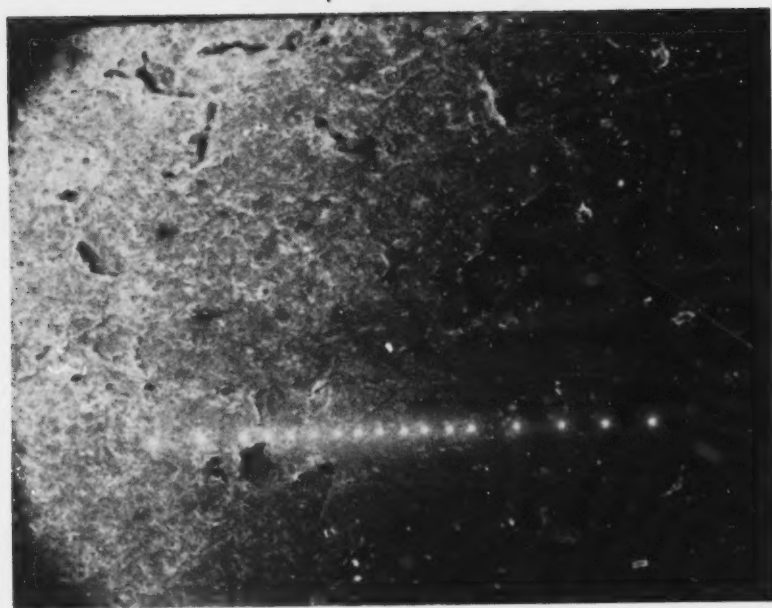


(10X)



(25X)

Figure 11. SEM photographs of Oxibak-H block specimen tested at 1375°C.



(25X)

Figure 12. SEM photograph of Oxibak-H block specimen tested at 1425°C.

TABLE 12. OXIBAK-H SLAG PENETRATION TEST AT 1375°C

Location	Mg	Constituent (%)		S	Al
		Si	Ca		
1	100.00	-----	-----	-----	-----
2	31.25	25.00	43.75	-----	-----
3	-----	-----	-----	-----	-----
4	-----	-----	-----	-----	-----
5	71.43	12.99	15.58	-----	-----
6	93.33	-----	-----	5.67	-----
7	91.30	-----	-----	8.70	-----
8	-----	-----	-----	-----	-----
9	81.25	-----	18.75	-----	-----
10	61.22	15.31	23.47	-----	-----
11	95.83	4.17	-----	-----	-----
12	-----	-----	-----	-----	-----
13	90.48	-----	-----	9.52	-----
14	100.00	-----	-----	-----	-----
15	10.43	26.32	63.16	-----	-----
16	25.00	30.00	35.00	-----	-----
17	57.47	11.49	25.29	5.75	-----

TABLE 13. OXIBAK-H SLAG PENETRATION TEST AT 1425°C

Location	Mg	Si	Constituent (%)		
			Ca	S	Al
1	68.11	11.15	6.81	3.10	10.84
2	90.91	1.82	3.64	3.64	-----
3	82.24	3.29	3.29	4.61	-----
4	38.67	33.33	10.67	-----	17.33
5	61.54	4.62	18.46	7.69	7.70
6	84.21	7.02	5.26	3.51	-----
7	89.36	4.26	-----	6.38	-----
8	87.88	4.55	3.03	4.55	-----
9	90.20	-----	-----	7.84	-----
10	87.27	1.82	-----	7.27	-----
11	92.90	-----	-----	2.73	-----
12	88.48	2.25	4.21	5.06	-----
13	91.53	3.39	5.08	-----	-----
14	90.00	-----	-----	10.00	-----
15	84.48	3.45	3.45	5.17	3.45
16	80.88	5.88	8.82	4.41	-----
17	80.29	7.30	3.65	8.76	-----

Korundal XD (HarbisonWalker Refractories) is a very high alumina refractory with the following chemical composition:

Al ₂ O ₃	90.8 %
SiO ₂	8.5 %
Fe ₂ O ₃	0.2 %
MgO	0.07%
Lime	0.07%
Alkalies	0.15%

Samples of the refractory at both temperatures exhibited no slag penetration (Figure 13) and no discernible refractory degradation (Tables 14 and 15). The cup wall above the slag pool was wetted and glazed. However, the wetting and glazing apparently had only a surface effect with no refractory attack, with the slag-refractory interface remaining sharp.

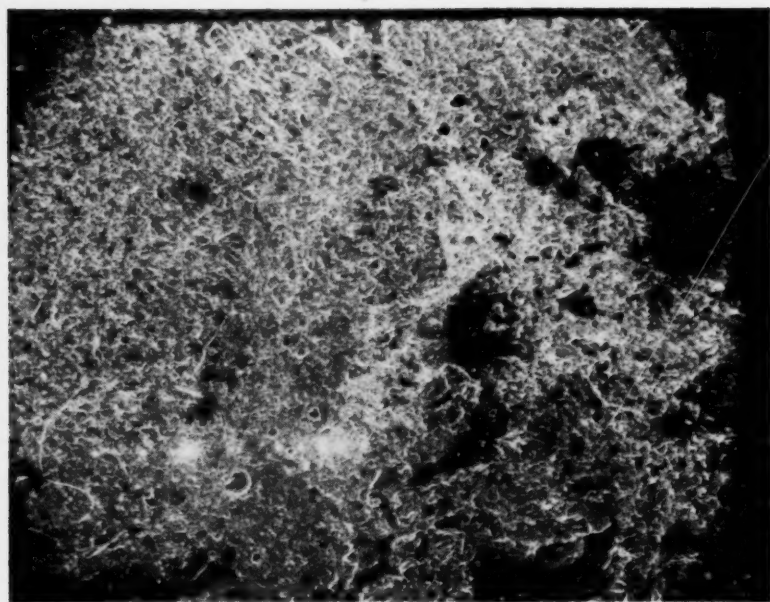
Refrax 20 and 50A (Carborundum Refractory Division) are high silicon carbide refractories with the chemical compositions listed in Table 16. Samples of both of these refractories at both test temperatures shows slight wetting of the cup wall above the slag pool and no penetration with slag separation from the cup after cooling (Figure 14). The attack on the refractory surface was very slight, and the slag-refractory interface remained very sharp. The constituent data in Table 17 confirms the visual observations.

Harbide (Harbison-Walker Refractories) is a silicon carbide refractory with the following chemical composition:

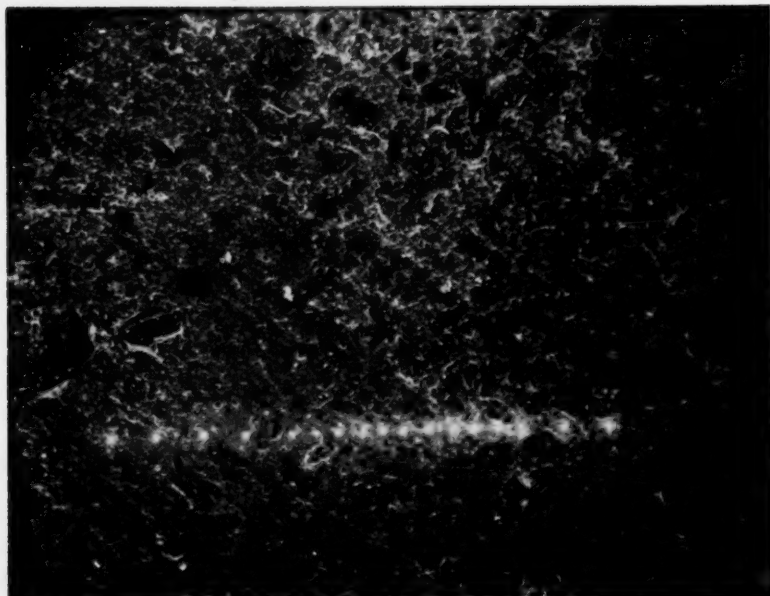
SiC	89.2 %
SiO ₂	7.3 %
Al ₂ O ₃	2.1 %
Fe ₂ O ₃	1.1 %
Alkalies	0.08%

Samples at both temperatures exhibited no slag penetration and slag separation from the refractory after cooling. The cup wall above the slag pool was wetted with a slight attack of the refractory surface. While there was evidence of some SiO₂ degradation, the slag-refractory interface remained sharp.

The slag penetration tests demonstrate that no single refractory can permanently serve as the lining for combustion chambers handling molten slag since the molten slag at high temperature will actively attack brickwork by taking it into solution. Because of its high alkali metal oxide concentrations, gas purifier slag will attack refractory more than will coal ash slag. The current design practice for facilities handling molten coal ash slag calls for water-cooled floors and walls to maintain low refractory temperatures.



(10X)



(25X)

Figure 13. SEM photographs of Korundal-XD block specimen tested at 1375°C.

TABLE 14. KORUNDAL-XD SLAG PENETRATION TEST AT 1375°C

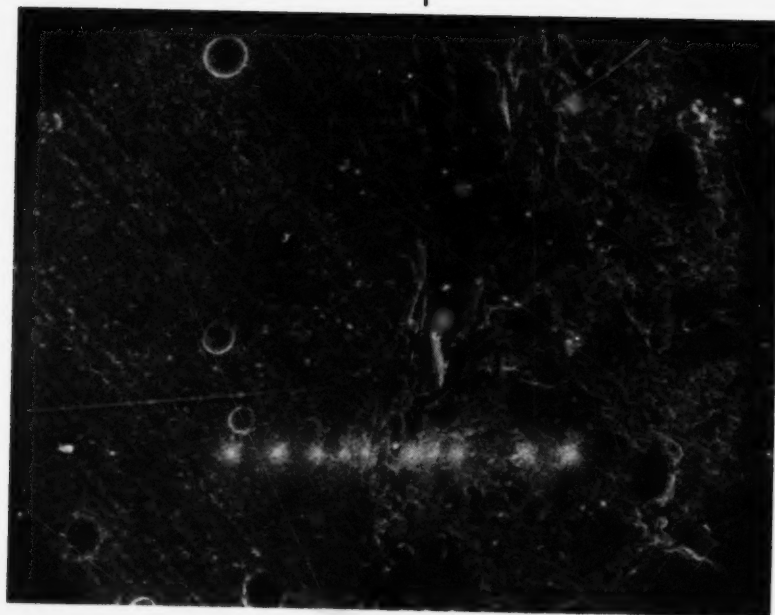
Location	Al	Constituent (%)			
		Si	Ca	Ti	Fe
1	27.17	51.09	20.65	1.09	----
2	30.30	50.22	19.48	----	----
3	100.00	-----	-----	----	----
4	62.92	31.46	3.37	2.25	----
5	83.58	12.69	3.73	----	----
6	80.00	16.84	3.16	----	----
7	71.87	23.61	2.46	2.05	----
8	73.81	26.19	-----	----	----
9	75.71	24.29	-----	----	----
10	76.36	23.64	-----	----	----
11	97.25	2.75	-----	----	----
12	81.45	11.31	-----	----	7.24
13	87.94	12.06	-----	----	----
14	86.54	13.46	-----	----	----
15	75.93	24.07	-----	----	----
16	88.00	12.00	-----	----	----

TABLE 15. KORUNDAL-XD SLAG PENETRATION TEST AT 1425°C

Location	Constituent (%)				
	Al	Si	Ca	Ti	Fe
1	21.78	51.32	21.94	3.84	1.12
2	23.70	27.08	20.57	11.72	7.03
3	55.33	34.76	9.91	-----	-----
4	100.00	-----	-----	-----	-----
5	81.92	18.08	-----	-----	-----
6	82.58	17.42	-----	-----	-----
7	57.64	42.36	-----	-----	-----
8	43.10	36.20	14.65	2.60	1.04
9	21.45	40.48	22.61	3.22	1.79

TABLE 16. REFRACTORY CHEMICAL COMPOSITION

Refrax 20		
SiC	79.15%	85.4%
SiO ₂	0.26	0.18
Al ₂ O ₃	0.64	0.64
Fe ₂ O ₃	0.66	0.66
CaO	0.30	0.30



(25X)

Figure 14. SEM photograph of Refrax-50A block specimen tested at 1375°C.

TABLE 17. REFRAX-50A SLAG PENETRATION TEST AT 1375°C

Location	Al	Si	Constituent (%)		
			Ca	Ti	Fe
1	19.47	48.66	26.79	3.21	1.87
2	18.74	51.79	25.16	2.74	----
3	20.67	55.01	18.24	2.62	1.30
4	21.40	54.29	18.68	2.38	1.06
5	20.67	57.63	17.32	2.00	0.96
6	-----	-----	-----	-----	-----
7	-----	99.29	0.44	-----	-----
8	-----	100.00	-----	-----	-----
9	-----	81.85	-----	-----	16.21
10	99.16	0.84	-----	-----	-----
11	1.00	-----	-----	-----	-----

Other Refractory Failure Factors

In addition to slag-refractory reactions, other major factors contributing to the failures of the refractory walls and baffles in the gas purifier were the high operating temperatures, constituents in the combustion gases, excessive thermal cycling and chocking, severe operating conditions, and excessive erosion.

While the gas purifier was designed to operate at an average temperature of 1370°C (2500°F) with a maximum of 1450°C (2800°F), the temperature frequently exceeded the temperature recording limit of 1650°C (3000°F) as evidenced by the thermocouple failures. However, since the fluid temperature of the gas purifier slag was 1360°C (2490°F) and the combustion temperature must be a few hundred degrees higher than that temperature to keep the slag fluid, the average combustion temperature should have been about 1650°C (3000°F) to maintain the slag at a temperature high enough to allow the fluid slag tapping process to occur. In addition, the slag-handling experience has established that to maintain a good slag flow the slag viscosity must be 250 poise or less, which, in this case, requires a temperature of at least 1482°C (2700°F).

The refractory-damaging constituents in the combustion gases included chlorine, hydrogen sulfide, sulfur dioxide, fluorine, and alkalies. In vapor form, chlorine, fluorine, and alkalies will reduce the life of many refractories at temperatures far below their normal temperature range. Hydrogen sulfide and sulfur dioxide are harder on refractories than the normal products of combustion.

The excessive thermal cycling and thermal shocking was due to inadequate control of the combustion air blown into the gas purifier. This inadequate control was in turn due to the improper monitoring and measuring of the combustion temperature and O₂/CO₂ concentrations.

The operating conditions were too severe for ordinary high alumina refractories. To have ensured reliable long-term operation in the slagging mode, the original gas purifier should have been lined with a pure alumina (99% alumina) refractory with a PCE of 42 (2015°C or 3659°F) and equipped with a water-wall bottom. Pure alumina refractories have a high resistance to the fluxing action of basic oxide and maintain a high module of rupture, crush strength, and load bearing capacity.

The particulate erosion was excessive because of the high particulate levels in the combustion gases and the high gas velocities. The erosion was most severe in the area where the gases in the crossover duct enter the gas purifier. In this area, the gas stream has a directional change and the gas temperatures are the highest since this is immediately downstream of the combustion air inlets.

Since the prototype gas purifier in the Landgard process operated in a nonslagging mode and all factors contributing to the failure of the gas purifier refractory were related at least indirectly to the slagging requirement, the failure of the gas purifier refractory is categorized as unique to the Baltimore plant.

DUCT REFRACTORY

The duct refractory includes the refractory for the crossover duct, the gas purifier exit duct, the boiler inlet ducts, and the scrubber inlet duct. In general, the refractory failures of these ducts were due to the following factors which are also common to the kiln and gas purifier refractory failures: severe operating conditions, excessive combustion gas temperatures, thermal cycling, material damaging gas constituents, thermal shock and structural spalling, and particulate erosion.

While most of the duct refractory has deteriorated substantially, only the gas purifier exit duct and some portions of the scrubber inlet duct refractory have been replaced. The original refractory in the gas purifier exit duct was a castable refractory anchored with metal hairpin anchors which was replaced with a high alumina brick refractory similar to the gas purifier refractory.

The crossover duct has two zones: the first extends from the feed hood to the combustion air inlet, and the second extends from the combustion air inlet to the gas purifier. In the first zone, refractory failures were minimal because the temperatures were too low for slagging and severe thermal shock. The refractory degradation in this zone was due to the erosion/abrasion from entrained particulates (over 45 kg/min), thermal cycling effects, and attacked by carbon monoxide, hydrocarbons, alkalies, and chlorides in the kiln-off gases.

In the second zone, the kiln-off gases have much higher temperatures and a greater turbulence. These conditions, coupled with the start-up and shutdown effects, cause severe thermal cycling and shock. Also, slag accumulates and liquifies in this zone, and the molten slag attacks and dissolves the refractory at the bottom of the duct. In addition, as the gases are discharged from the duct into the gas purifier, they undergo a directional change with the consequent increased turbulence which makes the particulate erosion/abrasion more severe.

If practical, the best means for minimizing the refractory failure in the second zone would be the installation of a water-cooled shell with a thin coating of 90 percent alumina plastic refractory on the inner surface. If the foregoing is not practical, the next best means for reducing the refractory failure is believed to be relining the duct bottom with pure fused alumina (99% alumina) and the duct top with a plastic 90 percent alumina material.

Gas Purifier Exit Duct

Excessively high temperatures caused the original castable refractory in this duct to sheet off at the tips of the anchors. Then the degraded refractory became highly susceptible to slagging and spalling. The refractory degrading was further intensified by particulate erosion/abrasion particularly at the turn in the duct.

When the castable refractory was replaced with high alumina brick, the sheeting off was eliminated and the slagging, spalling, and erosion were greatly reduced except in the duct bottom where the flowing molten slag eroded the brick by dissolving it. If a pure fused alumina (99%) were substituted for the high alumina bricks, it would reduce the slag effects to more acceptable levels and better resist the erosion/abrasion and spalling effects. Here again, the best means for minimizing the refractory failure would be to water cool the duct walls.

Boiler Inlet Ducts

Excessive temperature due to the lack of effective quench air control was the primary cause of the refractory failures in the boiler inlet ducts. To prevent slagging and fouling in the boiler requires that the temperature in the inlet ducts be carefully controlled by metering the quench air precisely and thoroughly mixing the quench air with the combustion gas. If the recommended water-wall construction in the crossover duct, gas purifier, and gas purifier exit duct were implemented, the amount of molten particulate entering the boiler would be greatly reduced, and consequently, the boiler slagging and fouling would be minimized.

Scrubber Inlet Duct

Refractory failures in the scrubber inlet duct were due to two causes: the first and the most damaging was the effect of the caustic and the water in the scrubber quench spary, and the second was the erosion/abrasion of particulates suspended in the combustion gas stream. The caustic reaction with the refractory caused the surface layers to swell and then structurally disintegrate. As water impinged on the hot refractory it caused severe thermal shocking. In addition, water penetrated the permeable refractory and caused spalling of the refractory. As the refractory degraded because of the foregoing damaging effects, it became more susceptible to the erosion/abrasion of the suspended particulates.

The refractory damage was reduced by eliminating the caustic in the spray and by controlling the spary so that water would not impinge on the refractory. The elimination of the spary itself, by either allowing the gas to enter the scrubber hot or quenching the gas with air, would likely have improved the situation but would have required increasing the capacity of the induced draft fan.

If the spary were eliminated with the consequent lesser susceptibility of the refractory to the particulate erosion/abrasion, periodic refractory patching with a very high abrasion-resistant plastic, such as Greenpak-90-PF, could have sufficed to maintain the structural integrity of the refractory.

The failures of the various duct refractories are considered to be unique to the Landgard process because they resulted from the conditions existing in that specific process.

SECTION 3

SLAGGING

The two major slagging problems at the Baltimore plant were slag hole pluggage and the slagging over of the boiler tubes at the boiler inlet. Pluggage of the gas purifier slag hole does not require immediate shutdown, but continuing slag build up over a long period in the gas purifier would eventually cause structural failure of the gas purifier. Boiler tube slagging does not require immediate shutdown but can damage boiler tubes, cause low energy recovery efficiency, and require excessive maintenance to restore the boilers to operation. Slagged tubes can also cause excessive pressure drop through the boiler and overload the induced draft fan.

The discussion in Section 2 of this report established that the gas purifier slag is very similar to bituminous coal slag. There is a large body of coal slag operating experience and data which will be referred to extensively in examining the problems of slag hole pluggage and boiler inlet slagging.

SLAG HOLE PLUGGING

Initially, the slag tap hole plugged frequently. A fuel oil burner was installed in the hole, but it did not prevent plugging and damaged the refractory in the slag tap hole. To minimize the heat loss, the size of the slag hole was reduced, and to form a concentrated slag flow, a dam with a V-notch on two sides was installed. At the same time, the operating temperature of the gas purifier was increased to 1370°C (2500°F). When these modifications failed to prevent slag hole plugging, another fuel oil burner and two propane burners were installed. These burners helped to keep the slag hole open, but they did not prevent slag hole plugging. To eliminate this problem, the city is replacing the gas purifier with a nonslagging afterburner.

It has been noted in Section 2 that the gas purifier was originally designed to operate at a temperature of 1100°C (2000°F). This should be compared to the average gas purifier slag softening and fluid temperatures of 1081°C (1978°F) and 1187°C (2169°F) respectively. Obviously, at the original design operating temperature the slag will not flow effectively.

Determination of Slag Tapping Characteristics

The two methods used to determine the slag tapping properties of a particular slag are the ash fusion temperature and slag viscosity measurements.

Ash Fusion Temperatures--

The melting temperature of slag is, due to its complex composition, not a single sharply defined point. As the temperature of a slag is increased, the ash begins to soften and becomes less viscous until a completely liquid state is reached. By definition, the various stages are called the "initial deformation temperature," "softening temperature," and "fluid temperature." The standard measure of initial deformation temperature is the temperature at which a prepared standard cone of free, individual ash particles begins to fuse or show evidence of deformation at the top of or apex of the cone as it is heated in a reducing atmosphere. The softening temperature (also known as fusion temperature) corresponds to an observed temperature at which the apex of the test cone of ash has deformed to the point where it assumes a spherical shape. This is the temperature at which the ash demonstrates a greatly increased tendency to agglomerate and adhere to heat transfer surfaces. The fluid temperature is determined by further heating of the ash test cone until the cone flattens and assumes a pancake shape. At this temperature, the slag can be expected to flow in streams and drip from heat transfer surfaces.

The standardized procedure for determining fusion temperatures calls for a reducing atmosphere in the testing furnaces; that is, the ash sample is heated through the temperature range from initial deformation to fluid with a slight deficiency of oxygen present--not an excess. In such an atmosphere, lower oxides are formed with some of the elements because of a lack of excess oxygen.

It is also important to note that the slag fluid point temperature with a reducing atmosphere is approximately 100 to 200°C lower than that obtained with a slag tested in an oxidizing atmosphere.

Slag Viscosity--

The Bureau of Mines has used both synthetic coal ash as well as actual coal ash to develop slag tapping characteristics prediction procedures from the slag chemical composition. In Figure 15 the chemical composition of the slag is used to determine the 250 poise temperature. This is a viscosity determined through experience to be the maximum viscosity for satisfactory slag tapping. Experience has also shown that this viscosity should not occur at a temperature in excess of 1400°C as seen in Figure 16.

Using this technique, the gas purifier slag has a viscosity of 250 poise at a temperature of approximately 1400°C (2575°F). According to Figure 16, the point for the gas purifier slag lies well within the satisfactory slag tapping region.

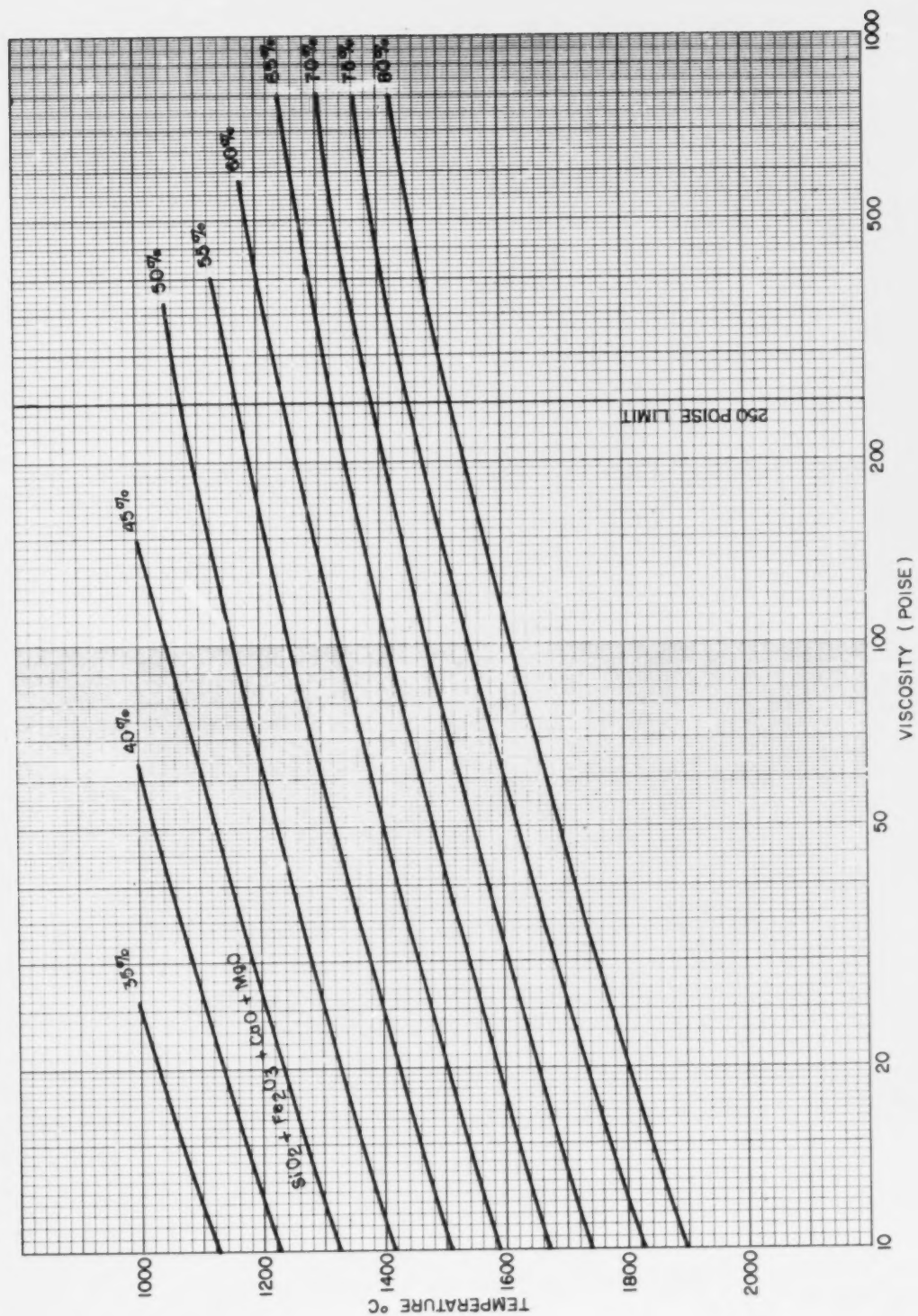


Figure 15. A plot of slag viscosity based upon temperature and chemical composition.

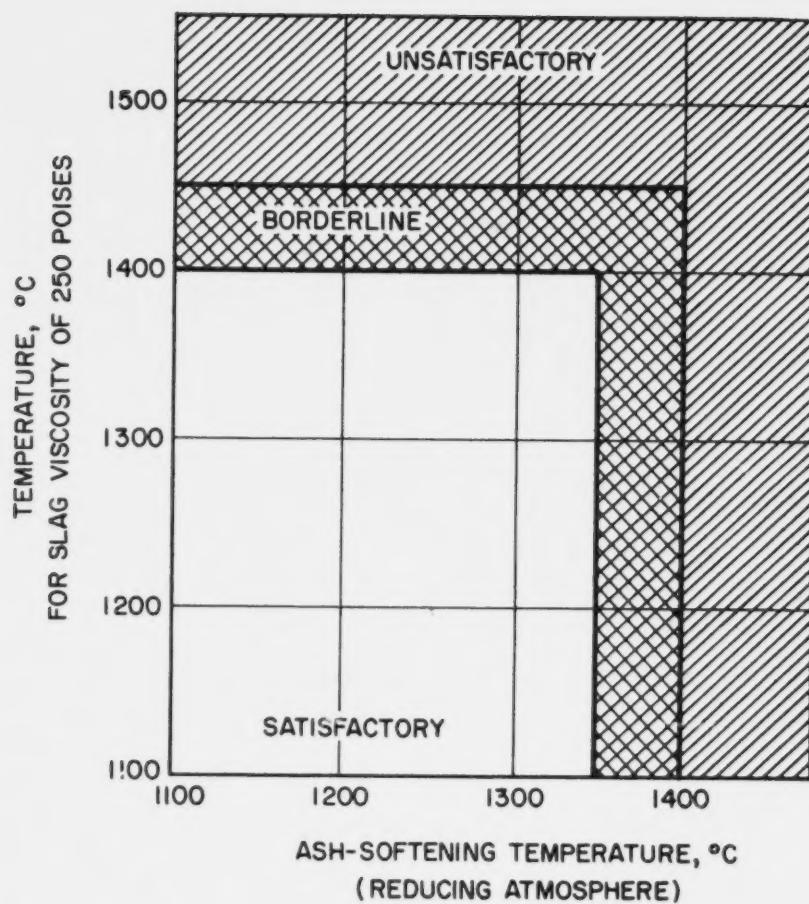


Figure 16. Slag temperature characteristics for satisfactory slag tapping.

A somewhat similar method for calculating slag viscosity based on slag composition has been developed by the U.S. Bureau of Mines and the Babcock-Wilcox Corporation. The slag viscosity calculations for bituminous type coal-ash slag, which is similar to the type found in the gas purifier, are predicted on the base to acid ratio, the silica/alumina ratio, and the ferric percentage of the slag using the following equations:

$$\text{Base to acid ratio} = \frac{\text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO} + \text{Na}_2\text{O} + \text{K}_2\text{O}}{\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2}$$

$$\text{Silica/alumina ratio} = \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3}$$

and;

$$\text{Ferric percentage} = \frac{\text{Fe}_2\text{O}_3 \times 100}{\text{Fe}_2\text{O}_3 + 1.11 \text{ FeO} + 1.48 \text{ Fe}}$$

The gas purifier slag has a base to acid ratio of 0.254 and a silica/alumina ratio of 3.2. In the absence of analytical data for Fe_2O_3 , FeO , and Fe , it is standard practice to assume a ferric percentage of 20. Using Figure 17 a slag temperature for 250 poise viscosity of approximately 1468°C (2675°F) is obtained. This is approximately 40°C (70°F) higher than the results of the preceding technique.

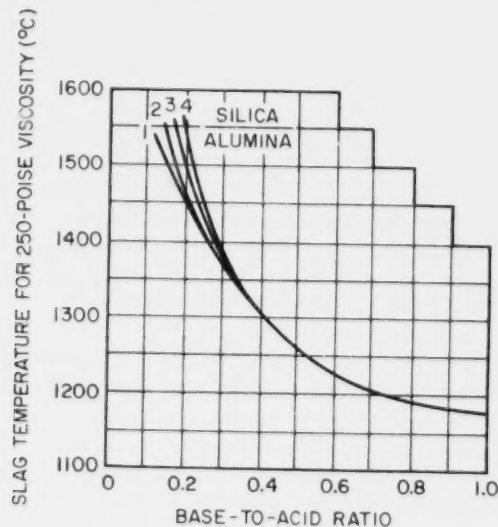


Figure 17. Slag viscosity based upon chemical composition.

In order to ensure a slag temperature of at least 1410°C (2570°F), the average operating temperature in the combustion chamber must be 1650°C (3000°F).

The fluid temperature (reducing basis) and the viscosity of the ash are design criteria for predicting the slag tapping characteristics. Since the tendency is to operate slag-tap combustors with low excess air and at high temperature in the vicinity of the slag bed, more of the iron content of the ash is in the ferrous form, and hence, the ash is more fluid. However, the ash viscosity, quite distinct from the ash-fusion temperature may be the determining criterion in predicting satisfactory tapping of a given ash.

The gas purifier should be operated in such a manner that slag conditions can be controlled by the oxygen-fuel ratio. Use of the initial deformation temperature (oxidizing basis) seems most appropriate as a design criterion for a dry-ash combustion chamber since the ash particles leaving the combustion chamber should be in a highly oxidized state. The combustion chamber should be operated to avoid reducing conditions anywhere in proximity to heat-absorbing surfaces.

If glass and noncombustibles are removed prior to entering the combustion process, the need for slag removal is minimized and more classical incinerator combustion techniques are appropriate. In this case, the combustion chamber should utilize the lowest possible gas velocities allowing the small unremoved noncombustible carry-over fraction to settle out prior to entering the boiler tube banks. Without question, the approach to be used must be the result of the total system requirements.

Since the slagging gas purifier is unique to the Baltimore plant, the plugging of the slag tap hole must also be considered unique to the Baltimore plant.

BOILER TUBE SLAGGING

Originally, slagging of the boiler was a significant problem. Slag coating of the boiler tubes thick enough to bridge the tube gaps occurred at the bottom of the tubes. The slag coating resulted when the spheroids of semi-molten slag stuck after impinging upon the tubes. As the coating would become thick enough to insulate the tubes, the slag surface would take on a slightly glazed appearance. No samples of this type slag deposit were available for examination at the time of this study.

Monsanto installed quench air ports in the gas purifier discharge duct to form a more friable deposit. The intent was to cool the slag particles so that the majority of the particles would not adhere to the boiler tubes and the remainder would form an easily removed deposit. The amount of air admitted did little to prevent adherence of the slag particles, but the slag deposits were rough as opposed to the glazed appearance seen previously.

Two approaches can be taken to prevent the formation of fly ash deposits on the boiler tubes. The first, is to remove the fly ash through the cyclone action of the gas purifier. The second approach is to cool the fly ash to a point where it will not adhere to the boiler tubes.

Fly Ash Removal

The gas purifier design was intended, with its tangential gas inlet and orifice-baffle wall, to operate as a cyclone and remove a high percentage of entrained slag cenospheres. The geometric design appears to have been good; although for cyclone operation, the tangential gas velocity was somewhat low, approximately 90 to 125 m/sec (300 to 400 fps). The following will show the inapplicability of the gas purifier configuration to remove the slag cenospheres without a reentrant type orifice-baffle wall exhaust nozzle and high gas rotational velocities.

Using average mass flow through the gas purifier of 2423 kg/min (5353 lbs/min), a gas purifier chamber cross-sectional area of 19.2 m^2 (214 ft^2), and a mean gas temperature of 1165°C (2130°F) and a mean gas molecular weight of 27.824, the mean gas density is 0.2355 kg/m^3 (0.0147 lb/ft^3). The drift velocity through the gas purifier chamber is 518 m/min (1700 ft/min). Therefore, the mean residence time of a particle is approximately 1.7 sec. Initial tangential velocity of gas through the crossover duct can be calculated in a similar manner.

$$\dot{m}_k = 1411 \text{ kg/min}$$

Crossover duct cross section exit area is $\approx 3.08 \text{ m}^2$

Gas mean molecular weight = 28.28

Gas mean temperature = 798°C

Then the gas density (ρ) is

$$\rho = 0.32 \text{ kg/m}^3$$

and the initial tangential velocity is

$$V_y = 1462 \text{ m/min}$$

Flow helix angle is approximately 19.5° from a plane perpendicular to the gas purifier axis.

The gas viscosity, assuming that air approximates the gas sufficiently, is 0.051 centipoise or 5.1×10^{-4} poise. From the mean tangential velocity, the angular velocity of the gas is 958 radians/min. The normal acceleration field of a particle entrained in the gas is $255.1 \times R \text{ m/sec}^2$. The settling

velocity for a particle, based upon Stokes law, is:

$$V = 2/9 r^2 g \frac{S_1 - S_2}{\nu}$$

where S_1 (the specific gravity of the solids) equals 2.36 and

S_2 (the specific gravity of the gas) equals 3.24×10^{-4}

Then

$$V = 2.623 \times 10^{-3} r^2 R$$

where r is the particle radius in microns, V is the settling velocity in m/sec and R is the particle location in meters from the rotational axis. Then the particle acceleration $A_p = dV/dr$ or $A_p = 2.623 \times 10^{-3} r^2$. Considering a 20 micron diameter particle $A_p = 0.2623$ for a residence time of 1.7 sec. From $D = 1 A_p t^2 + V_0 t$, where D is the initial particle distance from the gas purifier wall, the result is 0.379 m. This indicates that a particle 20 microns in diameter must be within 0.379 m of the gas purifier wall or it will not be centrifuged from the gas stream.

However, all particles 52 microns in diameter or larger should be removed from the gas stream.

Proper design of a cyclone type combustion chamber would provide an inlet and tangential velocity of at least 107 m/sec (350 fps). Assuming a chamber having a 3.05 m (10 ft) diameter and a 7.63 m (25 ft) length which is water cooled, then the maximum "g" field would be 7513 m/sec² (24,650 f/sec²). The "g" field equation is defined as

$$A_n = 4.923 \times 10^3 R$$

Assuming the same mass flow as presently used, the axial drift velocity for a gas temperature of 1650°C (3000°F) and a resulting gas density of 0.973 kg/m³ (0.011 lbs/ft³) is 31.9 m/sec (105 fps). A residence time period of 0.24 seconds results from the assumed chamber length of 7.63 m (25 ft). In a cyclone combustion chamber such as described, the flow helix angle would be approximately 16.6 degrees from a plane normal to the chamber axis. For the temperature noted, the gas viscosity would be approximately 5.86×10^{-4} poise. From Stokes law, the mean velocity is:

$$V_s = 4.4 \times 10^{-2} r^2 R$$

from

$$A_p = dV/dr$$

then

$$A_p = 4.4 \times 10^{-2} r^2$$

which yields

$$D = 2.2 \times 10^{-2} r^2 (t^2 + 1.159t)$$

If the residence time of 0.24 seconds is used, the D, the distance from the wall to be traveled by a particle of size r, is

$$D = 7.388 \times 10^{-3} r^2$$

Evaluating D for particles having an r = 10 micron then

$$D = 0.739 \text{ m}$$

This means that any 20 micron particle entering the cyclone within 0.74 m (2.4 ft) of the wall will impact the wall without the influence of an orifice exit nozzle. With the reentrant effect on an orifice type exit nozzle, the actual particle residence time is increased, temperature stratification effects of the high "g" field will cause a lower gas viscosity closer to the walls, and as a result of the higher settling velocities, particles down to approximately 5 micron will be eliminated from the cyclone exhaust. Additionally, the cyclone combustor as described previously is a lower maintenance item typically having an availability of better than 98 percent on line with power utilities including regularly scheduled annual maintenance.

An example of the accuracy of this analysis is seen in Figure 18 which is a pair of electron microscope photographs of agglomerated fly ash samples removed from the boilers. In Figure 18, one cenosphere is seen to have a diameter of approximately 70 micron with the remaining particles ranging from 5 micron to 45 micron with the most numerous size being approximately 20 micron. Figure 19 is a pair of optical microscope photographs of a loose fly ash sample at 10x and 100x. The particles are all cenospheres showing some agglomeration with the most common particle size being 20 micron.

The remaining fly ash not removed must be prevented from adhering to the boiler tube. Two obvious methods are: (1) remove the slag fraction from the process stream at some point before it reaches the boiler tubes or (2) cool the slag cenospheres to a temperature below their initial deformation point prior to reaching the boiler tubes. Initially, when slag accumulated on the boiler tubes, the gas purifier duct was modified with quench air ports to cool the slag particles. This was partially successful, but at the present time slag still tends to accumulate. Therefore, since at the present time it is impractical to remove the slag fraction from the process stream, more effective cooling techniques are needed.

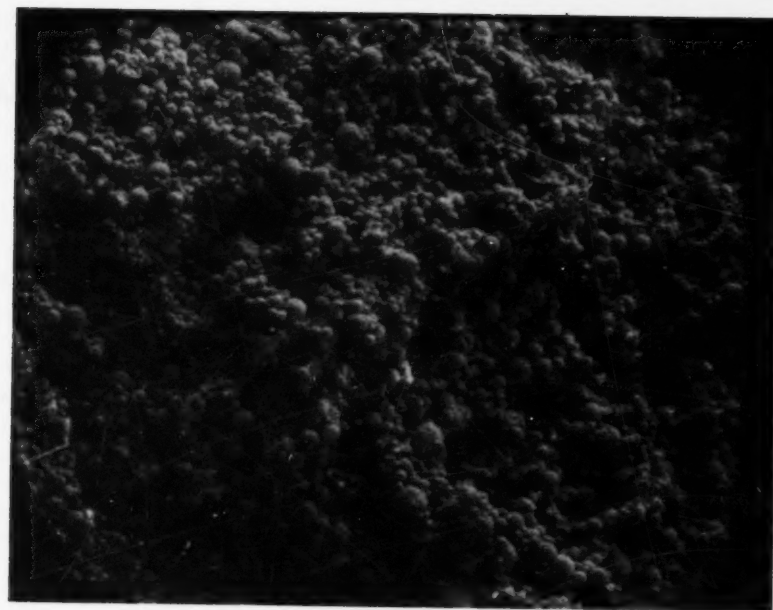
Fly Ash Cooling

Surface cooling modes for fly ash particles are radiation and convection.

There is only a relatively short distance of approximately 9 m (30 ft) from the gas purifier discharge duct quench ports to the first set of boiler tubes. The slag particles do impinge on the boiler tubes but do not fuse. This is indicative of a slag particle temperature approximating the initial deformation point. Heat transfer calculations indicate that radiative heat transfer to the duct walls exceeds conductive or convective transfer to the cooled or "quenched" gas stream by several orders of magnitude. The

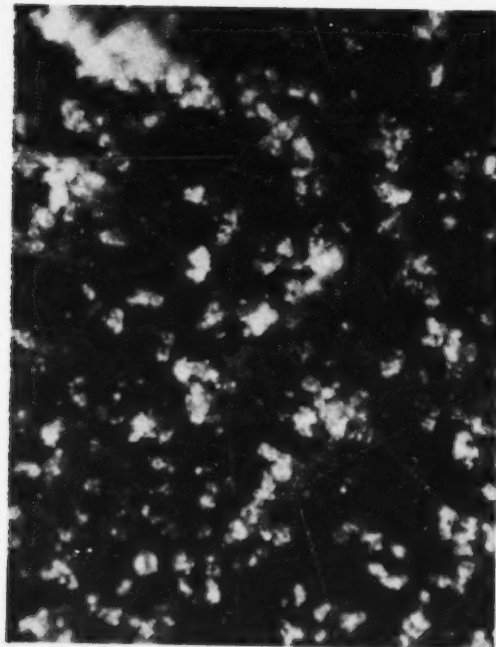


21 X



105 X

Figure 18. Scanning electron microscope pictures of fly ash.



10 X



100 X

Figure 19. Optical microscope pictures of fly ash.

conclusion drawn from this is that the quench air admitted to the gas purifier duct would be more effectively utilized if it were used to cool the duct walls. If the duct walls were cooled to some 50°C below the initial deformation temperature the slag particles should not adhere to the boiler tubes or could be removed from the boiler and/or ducts through the use of ash blowers. Another technique used by the power industry to protect boiler tubes from collecting ash deposits is to install slag screens in front of the first boiler tube rows. The screens are not screens in the normal sense of the term but instead consist of up to six rows of water-cooled tubes. Generally, the slag screen tubes across the boiler inlet are on 25 cm (10 in.) centers, and from front to rear on 12 cm (5 in.) centers. Alternate tube rows are staggered with a resulting minimum spacing of 19 cm (7.5 in.).

As the slag particles pass the cool tubes, their temperature is reduced by radiative heat transfer to the point that they will not adhere to the downstream boiler tubes.

Soot blowers must be used to remove the resulting fly ash from areas of repose since, if this is not done, the fly ash will, over a short period of time, slowly sinter into a consolidated mass of considerable strength, depending upon sintering time, temperature, and the ash characteristics.

The decision of the City to use a nonslagging afterburner should alleviate the slag build-up problem since slag softening temperatures will never exist.

An analysis of the problem reveals that this problem is unique to the Baltimore plant since the prototype Landgard unit had a nonslagging afterburner.

SECTION 4

CONVEYORS

Since the plant operation requires that material flow continuously through all processing equipment, the plant must be shut down whenever any one of the principal conveyors fails. The principal conveyors are the storage pit and the shredder feed conveyors, the screw conveyors, and the residue quench tank drag conveyor.

STORAGE PIT AND SHREDDER FEED CONVEYORS

Because these conveyors initiate the flow of refuse to all the downstream processing equipment, the shutdown of these conveyors would cause a total plant shutdown.

Shear pin failures, link failures, and the shredder interlock have caused the numerous shutdowns of these conveyors.

In the original equipment design there were several regions in which the material could accumulate, build up, and eventually jam, causing shear pin failure. This problem was particularly severe at the transfer point between the horizontal pit conveyor and the shredder feed conveyor. The conveyors are so close that the pusher bars on the horizontal conveyor tend to capture material that has just fallen onto the shredder feed conveyors and push it backward into the recessed pit below the conveyors where it can accumulate and eventually cause jamming. A better approach for any new system, but one which would be impossible to retrofit, would be to increase the vertical separation of the hopper pit and shredder feed conveyors with a slide trough between them to direct the waste onto the shredder conveyors without spillage. It would be necessary to have sufficient clearance between this trough and the hopper pit conveyors so that the returning pusher bars could not force material into the recessed pit area.

Jamming also occurred at the return run of the shredder feed conveyor where waste would accumulate. This problem was solved by installing a drop-out chute on the return run of each conveyor which discharged onto the shredder discharge conveyor.

On one occasion, improper shear pin installation resulted in major system failure when a solid steel object jammed in a pinch point of a unit. The shear pin did not fail and when one of the conveyor links failed, the drive motor continued to pull the pans through the gallery so that major

damage to the pans, links, and shafts occurred. This could have been prevented if the manufacturers had allowed for sufficient access for installing cotter pins on both sides of the shear pin.

The accumulation and wedging of noncompressible materials between sprockets and drive chains caused a cantilevering of chain links as they passed over the sprocket. Any link design would ultimately overstress and fail as a result of such a cantilevered motion. The links of this particular conveyor system are particularly susceptible to such stress failure. Link failure of this sort on one side of the conveyor does not result in sufficient force to cause shear pin failure. Instead, when one link fails it tends to cause other links down the line to become overstressed and also fail so that a simple failure cascades into a major system failure with extensive loss of operating time.

The problem appears to have been solved by enclosing the head sprocket and chain within a steel guard to prevent material from accumulating between the sprocket and chain. Conceivably, material could accumulate in the links and be carried into the sprocket area under the steel sprocket guard, but the rubber aprons now installed seem to suffice for preventing material side spillage and accumulation.

These conveyors have failed to uniformly load the shredders causing frequent overloading of the shredders with the subsequent shutdown of the conveyors. Leveling bars were added to both pit conveyors in an attempt to maintain a uniform waste load on the conveyors. These bars caused jams and subsequently resulted in shear pin failure.

The storage pit and shredded feed conveyor failure are considered to be typical of solid waste processing since the equipment is typical of solid waste processing systems and the failures were due to equipment design. System vendors are currently modifying their designs to reduce these problems.

SCREW CONVEYORS

When the screw conveyor system or any part of it fails, the entire plant must be shut down to prevent the accumulation of slag frit in the seal tank which would quickly plug the slag tap hole.

Originally, the spillback conveyor and the slag frit conveyor were one unit which ran the entire length of the seal tank bottom and were driven by a single motor. When the screw flexed severely during operation, the screw was divided at the intersection of the transfer frit conveyor, and hanger bearings and drive motors were installed. The hanger bearings were not located on the end of the conveyor and blocked the flow of the large unexpected slag balls. The hanger bearings were subsequently moved to the end of the conveyor.

The screw conveyors sheared pins regularly, and the strength of the shear pins was greatly increased to keep the system operating. However, the increased shear pin strength prevented the performance of a motor protection

function and the system was often inoperable due to motor overload. After the motor size of each conveyor was increased, the screws of the slag frit and the transfer conveyors were severely damaged and were replaced.

The spiral edges of the screw conveyors were thickened and the screw pitch was decreased from 45 degrees to approximately 10 degrees. With the decrease in pitch of the screws, a more dense, more compact material could be moved without damage to the screws or motors or constant shear pin failure. Overloading still occurs, and it is expected that a larger motor is required for the transfer conveyor. Since the design changes, pin shearing and motor overloading continued but occurred less frequently. The City of Baltimore is planning to eliminate these conveyors by using a nonslagging afterburner.

Most of the failures were caused by the large slag balls discharged from the slag tap hole and the extreme underestimation of the slag bulk density. Large, unfritted slag balls conveyed along the bottom of the tank would jam against the side causing the tank to flex slightly and the shear pins to shear. It was then necessary to clean out the tank and replace the shear pins. Another reason that the original screw conveyors failed was because the original design bulk density was half of the actual bulk density.

Since the slagging gas purifier was unique to this specific installation, the screw conveyor failures are unique to the Baltimore plant.

RESIDUE QUENCH TANK DRAG CONVEYOR

Whenever the single drag conveyor to discharge the solid residue from the quench tank in the kiln fire hood failed, the entire plant had to be shut down because of the single-line operation of the thermal processing area.

In the early operating period of the plant, the drag conveyor frequently failed, jammed, or overloaded when large pieces of fused slag were discharged from the kiln. Although not related to the design conditions for the conveyor, large pieces of fallen kiln refractory also jammed and overloaded the conveyor.

In the original design, the return run of the drag conveyor was within the quench tank with all slag particles and other residue expected to fall through the apertures between the drag flights of the return run and then onto the tank floor where the flights of the drag run would push the residue up a dewatering incline to a discharge point. Consequently, oversized slag balls jammed the conveyor by lodging between the return and drag run flights or by lodging in a return run aperture to be carried along by the flights and chains to the tail sprocket where it would wedge at the quench tank wall. In one instance, a slag ball lodged in a return run aperture and pulled off the entire tail sprocket assembly. In addition, large balls falling freely onto the return run damaged the drag flights and overloaded the conveyor system, particularly, as mentioned above, the shear pins and the chain links. As the chain links stretched with the constant overloading they had to be adjusted regularly to prevent them from jumping the head sprockets and to facilitate smooth start-up.

Consequently, the drag conveyor system was redesigned so that the return run would pass over the kiln fire hood and then down to the original tail sprocket. In addition, the chains and drag flights were strengthened and the motor size was increased. Then, after residue began accumulating on top of the kiln fire hood as the wet residue adhering to the flights and chains dried and fell off during the overhead pass, notches were cut into the drag flights to minimize the subsequent spillage and to prevent cans from wedging between the chains and the head sprockets.

The foregoing redesign and subsequent modifications remedied most of the conveyor malfunctions. While pin shearing was minimized and the chain links generally remained intact, the drag flights still required extensive repair and replacement. Although the drag conveyor tension still had to be adjusted regularly, the adjustment was a minor effort.

Some of the conveyor failures could have been caused by the high bulk density of the residue which was twice the design value. However, most of the failures occurred when large residue slag balls or other large objects such as kiln refractory were discharged from the kiln. One mode of failure due to these large slag balls was described earlier. The other mode of failure, which continues to cause this conveyor to fail, results from the large concentrated loads that these slag balls put on the conveyor. The drag conveyor was designed for a uniform loading of all the flights rather than a concentrated load on one flight. While individual slag particles were expected to have an average size of about 10 centimeters (4 in.) with some occasionally up to about 60 centimeters (24 in.) in length, slag balls as large as 1 by 2 meters (3 by 6 ft) were seen in the residue quench tank.

Since the drag conveyor failures were caused primarily by the larger-than-expected slag balls and a facility could be designed to handle such residue, these failures were considered to be unique to the Baltimore plant.

SECTION 5

RAM FEEDERS

The ram feeders advance refuse into the kiln for thermal processing and, if the ram feeders are inoperative, the entire plant must be placed on standby or shutdown. The ram feeders have experienced ram jams, snout deformation and failure, and hydraulic hose damage in their short operating history.

RAM JAMS

Refuse feeder jams are an extremely critical problem because if a jam cannot be cleared the facility must be shut down to allow the jam to be cleared manually from inside the kiln. In addition, when feeding of refuse through the tubes is halted for any reason, there is the possibility of fire in the refuse plug since the feed tubes are not cooled and the refuse plug is in contact with the hot tube walls.

Ram jams have typically occurred in three locations: the end of the feeder tube snouts, the tube air seal deflection plates, and the feeder tube entrance.

Ram jams are the result of some obstruction to the smooth flow of refuse in the tubes and the inherent compactability of refuse which allows refuse flow to be stopped at some point and further refuse feeding to compact the initial plug to the point where the feed tube is jammed. Ram jams which originate at the tube discharge ends are generally believed to be the result of tube end deformation.

Some ram jamming occurred at the internal deflection plates which were installed in the feed tubes to prevent air leakage through the refuse plug into the kiln. Each tube originally contained two metal wedges which were intended to compress the refuse plug as it progressed through the feed tube. The intent was to provide a progressively denser refuse plug by decreasing tube area as the refuse passed the wedge apex thereby reducing the leakage of air through the refuse plug. Although the wedges did perform the assigned task, they provided an obstruction which would periodically cause a jam in the feed tubes. Removal of the wedges naturally removed this source of jamming but also allowed a higher leakage air flow rate.

Jamming of the rams at the inlet to the feed tubes also occurred. This type of jamming was originally caused by refuse overloading one ram hopper at the inlet. Subsequently, a flow splitter was installed to evenly distribute

the refuse between the two ram hoppers. This reduced the frequency of jamming but did not eliminate it. The remaining cause of ram jamming at the inlet to the feeder tubes can be attributed to a combination of the compactible nature of the refuse feed stock and the feed tube inlet geometry. The inlet geometry must be changed to remove the short, steep angle of the entry ramp where most jamming occurs. It is felt that improvement in operation could result from changing the entrance configuration to one where the large piston or ram enters the tube a short distance rather than stopping even with the forward wall of the hopper. The entry should be a shear configuration with clearance around the ram as it enters. This configuration would appear as a piston entering a cylinder. At the end of the short cylindrical tube section, the feeder tube would have a gently tapered cone shape transitioning from the inlet cylinder to the final feed tube cylinder. A modification entailing considerable expense and difficulty would be to provide access to the feeder tubes for clearing ram tube jams which will, in all likelihood, continue to occur although the inlet configuration may substantially reduce the frequency.

Because rams have effectively been used to feed solid waste to other systems, the Landgard prototype being one of them, this problem is believed to be specific to the geometry of the equipment installed at the Baltimore plant.

SNOUT FAILURE

Failure of the ram feeder snouts is considered to be a critical problem because of the resulting ram jams and equipment damage which require a complete shutdown of the process. Only when the kiln can be entered can the ram jam be cleared and the feeder tubes be repaired.

The earliest ram feeder tube or snout failures were the most damaging. The original feeder tubes or snouts were constructed of stainless steel and were water cooled. During the first heat cycle, a heavy hammering was heard coming from the feeder tubes. The tubes had ruptured at the tube wall seams and spilled the cooling water onto the refuse and hot refractory of the kiln. The tubes were replaced with new uncooled tubes of 316 stainless steel. The uncooled tubes rapidly deformed in the high temperature environment of the kiln resulting in ram jams on numerous occasions.

The cooled tube failure experience appears, by the manner in which the equipment behaved and nature of the failure, to have been the result of several problems. Most obviously, there was a manufacturing defect which probably had two elements. The first was one or more misplaced baffles short circuiting the available water supply. The second was a cooling passage cavity with an obstructed inlet or outlet effectively becoming a partially sealed area. As a result, water was allowed to fill the cavity and be turned to steam. When the steam pressure subsided, the cavity would again fill with water to restart the cycle. An operating problem was also found to exist complicating the situation. The cooling water flow was supplied from an undersized main, but the extent of contribution of this situation cannot be evaluated.

Problems encountered with the uncooled feed tubes had their origin in two areas. First, the material specified had only marginal strength and second, the kiln temperatures experienced were higher than anticipated resulting from process control problems. The use of a rolled alloy did provide some strength margin as did the ribs and stiffeners.

The discharge ends of the tubes were eventually cut to a 45° angle to reduce the occurrence of ram jamming. The internal deflection plates used to produce an air seal with the extruded refuse were also removed for the same reason. The feeder tubes or snouts presently operate in spite of severely deformed discharge ends but do not produce good air seals and will require eventual replacement. The result of the high air leakage rate is excessively high feed hood temperatures which contribute to rapid refractory deterioration and continued feeder tube distortion as well as volatilization of heavy metal fractions and poor process control.

Returning to a watercooled set feeder tubes will accomplish two objectives. The first is to provide a feeder tube capable of surviving the high temperature environment and, the second is to provide a duct cool enough to prevent heating of the refuse plug to the point where it can ignite when refuse feeding is stopped for any reason. There is no reason that a water-cooled tube cannot successfully survive in the kiln environment.

Water-cooled exhaust nozzles and combustion chambers have been successfully operated for many years in environments where the heat flux is at least an order to magnitude higher than that experienced in the kiln. Care in design and fabrication should prevent failures of this nature from occurring.

The tube failures experienced are considered to be a characteristic unique to the Baltimore Plant. The reasoning for this is that by replacing the tubes with water-cooled tubes having proper design, accurate manufacture, and an adequate coolant supply, failures should not occur.

HYDRAULIC SYSTEM

The ram feeder hydraulic system is the heart of the kiln refuse feeder system. Any disabling problem encountered by the hydraulic system will stop operation of the ram affected. Normally, a disabling problem can occur to one ram and still permit continued processing operations for a short period of time with the second ram while repairs to the first are made. A failure in the entire hydraulic system would precipitate a plant shutdown.

The hydraulic fluid was originally routed to the hydraulic cylinders through hard wall tubing having fitting type joints between tube sections. The frequent shift from normal pressure to high pressure (10,350 kPa to 20,700 kPa) to clear ram jam represented a shock loading causing leaks. Frequent leaks from split tubing and ruptured fittings were continuous problems during system start-up. Changing the fluid lines to flexible hose prevented tubing fatigue but the hoses and connecting fittings still remain a problem. Frequent leakage at the pump and actuator cylinder seals is a source of high cost for lost hydraulic fluid and seal replacement maintenance.

The hydraulic fluid used in the system is Monsanto's Pydraul 50-E. This is a high-temperature capability, synthetic, ester base fluid. This hydraulic fluid is typical of ester base fluids, requiring stringent control of the materials in contact with it. The aviation turbine industry has a long history of successful experience with these types of hydraulic fluids and, hence, their use cannot be considered unique or experimental. Material compatibility is definitely acknowledged to be a concern, but seal materials such as teflon, viton, and other fluorinated hydrocarbons have been used with complete success. Comments by technicians and maintenance men to the effect that the fluid "eats up the seals" is typical of the reaction occurring when normally available commercial seals, which are noncompatible type materials, are used in contact with ester base oils and hydraulic fluids.

It seems highly likely that the ruptured hoses are the result of non-compatible materials, since the use of such hoses with similar hydraulic fluids is standard operating procedure in the aviation turbine industry. No information was readily available to determine the flexible hose material composition, therefore, evaluation of the compatibility of the hose and fluid was not possible.

The situation is compounded by the ready access of glassy grit to the seals and seal surfaces. Such materials enter the actuator areas with ease and, when in contact with the wetted seal surfaces, stick and rapidly abrade the seals.

Several alternatives are possible means of improving service life. Clearly, only compatible seal and hose materials should be used during maintenance, and special care should be taken to ensure installation of only those type materials.

Abrasion of hoses and seals can only be prevented by eliminating the glassy grit from contact with those parts by either protective devices or by separating the glassy fractions from the refuse before it has entered the feeder.

Failure of hydraulic hoses and seals as well as pumps and other components of the hydraulic system must be expected at least on an infrequent basis. Because of this, it is only realistic to provide safe access to all parts of the hydraulic system for repair and maintenance while operation of the second system continues. At the present time, this is not possible. Elimination of the causes of feeder tube jamming would greatly extend the life expectancy of all components by eliminating the need for the high pressure override to clear jams which cause shock loading.

Problems which have occurred concerning incompatibility of materials can be considered typical of any hydraulic system where sufficient care has not been taken to assure use of compatible materials. This problem can occur in any industry or usage. Although the component damaging hydraulic shock loading used to clear jams results from the basic characteristic of refuse, the specific feeder design enhances this problem in the Baltimore Plant. The presence of glassy grit in municipal refuse should be expected unless the refuse is processed to eliminate this fraction.

SECTION 6

STORAGE AND RECOVERY UNIT

While failure of the storage and recovery unit will not immediately cause a plant shutdown because refuse processing can continue using the bypass chutes, these chutes have a tendency to jam and are not considered reliable. More importantly, the storage and recovery unit has not been able to sustain the rated output capacity, thereby decreasing the throughput and increasing the net processing costs.

Shortly after start-up it became apparent that it would be difficult to recover the refuse stored in the storage and recovery unit. Many modifications were made in attempting to solve this problem: (1) the bucket sweeps were operated at high speeds, (2) teeth were added to the buckets to dig into the pile better, (3) the four 10-bucket chains were changed to three 20-bucket chains to allow more buckets to contact the pile, (4) the size of the center cone was also increased to allow more buckets to contact the pile, and (5) a rotary distribution chute was added to the top of the unit to distribute the waste evenly around the center cone.

While these modifications improved the recovery somewhat, the unit did not operate satisfactorily. In addition, the high operating speed caused excess wear of the bucket shoes and the floor of the unit. Because of these problems, the city made some major modifications: (1) a large door was installed to allow access by a bulldozer, (2) the bucket chains and the center cone were removed, and (3) the distribution chute was set to discharge directly to the outfeed conveyor. After numerous jams occurred on the out-feed conveyor, the city terminated the use of this equipment.

The basic cause of these problems was a lack of understanding during system design of actual service conditions which led to improper choices of design parameters and materials specifications. The design density of the shredded refuse was set at too high a value which led to the selection of a live bottom design that was not capable of providing the desired feed rate at the design operating parameters. Attempts to compensate for this by running at four times the design bucket speeds greatly increased equipment wear.

The decision to store and process unclassified, unseparated refuse contributed to the operation problems by (1) introducing large quantities of fine glass particles into the unit where they tended to filter through to the floor causing extreme abrasive conditions and excessive wear on the floor and the bucket wear shoes, (2) allowing wire and large pieces of textiles which went through the shredders to act as reinforcements tying the refuse

together into a mass that was difficult to tear apart for feeding, and
(3) preventing any control of moisture content in the shredded refuse.

The installation of the large cone in the center of the silo to move the pile out from the center for better bucket contact was a good decision. However, the choice of the cone shape was poor since the sloping sides of the cone tend to support the matted pile instead of causing it to drop. This is especially true when wire and textile pieces tie the pile together. A cylindrical shape with a short cone section at the top would be more effective in causing the pile to drop.

The floor was constructed of concrete with standard limestone aggregate with surface dusting of metal particles. The concrete had a compression strength of 27,600 kPa (4000 psi) instead of the specified 41,400 kPa (6000 psi). This type of floor has proven itself to be completely inadequate for the abrasive conditions and high bucket speeds encountered in this operation.

The original design specified a refuse bulk density of 400 kg/m³ (25 lbs/ft³) and provided four chains of 2-ft buckets, a bucket speed of approximately 13.7 m/min (45 fpm), 2 sweep drive motors, and a single discharge conveyor across the diameter of the floor. The measured bulk density of the refuse has run 200 kg/m³ (12.5 lbs/ft³) and less. To solve the problem of an inadequate recovery rate, the silo manufacturer has recommended the installation of from four to six radial collection conveyors, bucket chains of 4-ft buckets, bucket speeds of 13 m/min (43 fpm) or less, and 4 sweep drive motors. Adoption of these recommendations should improve the feed rate and reduce the wear.

To solve the floor wear problem, the equipment vendor recommended a surface of flint aggregate in an epoxy binder which would probably not be adequate in this operation. Experience with this topping at the Ames, Iowa, facility shows that the epoxy is quickly picked out by the abrasive glass particles and the brittle aggregate is easily crushed.

The wear resistance of the floor can be improved by restoring the concrete to a level 2.5 cm (1 in.) below the working level and topping it with at 2.5 cm (1 in.) layer of Anvil Top®, a product of the Master Builders division of Martin-Marietta Corporation. This material has been in use in industry since 1952 and has demonstrated exceptional resistance to abrasion and impact. Anvil Top 929, which can be poured, finished, and cured the same as concrete, consists of 90 percent cast iron aggregate and develops 82,800 kPa (12,000 psi) compression strength.

Tests conducted at the Baltimore facility showed that wear shoes made of Astralloy provided greatly improved service life for bucket wear shoes. These should be used on all buckets.

A very critical item in reducing bucket shoe and floor wear is the removal of glass from the refuse prior to storage of the refuse in the storage and recovery unit. Since much of the glass is pulverized into small particles by the shredders, it makes an ideal grinding medium when allowed to

collect on the floor. The fine glass particles also cause high wear rates in the bearings of the ring wheels and other moving parts.

The fact that much of the glass is so small makes removal a fairly simple matter. A trommel, with screen openings of 19 to 25 mm (0.75 - 1.0 in.) would remove a large percentage of the glass particles when located between the shredders and the storage and recovery unit. Additional benefits of glass removal would be a large reduction in slagging problems in the kiln, gas purifier, ducts, and boiler inlets and a possible reduction in the fly ash particles in the stack gases.

Introduction of a counter-current flow of air through the trommel would facilitate dust collection and reduce the moisture content of refuse.

Moisture measurements, taken on the feed, varied from 8 percent to 40 percent. A moisture content of 40 percent is approaching that of some dewatered sludges and is a condition which tends to promote packing or matting and creates problems in moving material easily. On the other hand, a low moisture content usually results in a material that tends to stay loose and move easily.

Using a trommel before shredding is another alternative which has the additional advantage of reducing shredder wear and the amount of waste requiring shredding. The operation of the trommel may, however, increase the net processing costs.

In summary, the performance of the storage and recovery unit can be improved provided:

1. The live bottom is reworked to incorporate the recommendations of the manufacturer with at least four conveyors and a 2.5 cm (1 in.) topping of Anvil Top.
2. The shredded refuse is trommeled prior to storage to remove abrasive materials and to control moisture.

This unit is used in many other refuse handling facilities, but since the Landgard process is the only process where this unit is used to store primary shredded, mixed municipal solid waste, the problem must be considered typical of the Landgard process.

SECTION 7

RESIDUE SEPARATION MODULE

A shutdown of the residue separation module does not have a direct effect on the operation of the rest of the system since a bypass gate allows the residue to go directly from the residue drag conveyor into trucks for disposal. However, the problems encountered in this module were so numerous and extreme that a discussion of them is justified.

The operating history of this module is very limited due to the short period of time that it was operated. In general, the equipment did not separate the residue cleanly and required considerable modification. This module has been dismantled by the city and the residue will be sent to the landfill without separation.

Design deficiencies caused a number of operational problems; most of these deficiencies have been corrected. The chain drag in the flotation unit was designed to push rather than pull the bottom material. Adequate access was not provided for cleaning and maintaining the flotation unit, and additional access doors had to be cut in the side of the tank. Many of the flumes, overflow wiers, and conveyors were undersized. Inadequate drains were provided for various tanks and no clean-out provision was provided in pipes carrying slurries. The sludge line from the thickener frequently plugged until a recycle line was installed. A nonweatherproof motor was mounted outdoors. A grit settling box had no provision for removing collected grit.

The main cause of problems in the residue separation module was the lack of satisfactory process control in the kiln which results in the residue being either overprocessed or underprocessed. Overprocessing results in high temperatures and the formation of refuse slag balls which jam or damage the equipment. Underprocessing allows materials such as rags and plastics to jam and blind pump screens. Indications are that when the pyrolysis process is operating properly the residue can be handled by the separation module with a minimum of problems. Clumps of wire and crushed cans, which survived the shredder, still present problems. The materials which constitute the major portion of the residue contribute heavily to the problems of good process control in the kiln which, in turn, cause many of the residue separation problems.

The tendency of the glass in the trash to soften and form slag balls at relatively low temperatures contributes to process control problems by making it more difficult to achieve good pyrolysis without slagging. In

addition, the pyrolysis process lowers the resale value of separated metals significantly, reducing revenue potentials proportionately. Fine glass and metal particles in the residue are highly abrasive and cause wear problems throughout the system. Wire, crushed cans, and slag balls cause jamming and damage to equipment and plugging of pumps and pipes.

The best solution to the problem is to separate metals and glass from the trash prior to pyrolysis. Pre-pyrolysis separation would necessitate a redesign of the residue quench tank to provide removal of floating char which presently sinks due to the weight of the glass and metal in the residue. The benefits of pre-pyrolysis separation would include:

1. Improved process control in the kiln.
2. Greatly reduced erosion/abrasion in pumps, pipes, duct work, the storage and recovery unit, the induced draft fan, and the refractories.
3. Greatly reduced slagging and slag build-up throughout the thermal processing and energy recovery modules.
4. Potential reduction in particulate emission.
5. Increased revenue from separated materials.

Because the residue separation module is unique to the Baltimore plant, so are the problems of operating the module.

SECTION 8

SYSTEM PRESSURE OSCILLATIONS

The thermal processing system is designed to operate at sub-atmospheric pressure to prevent the escape of process gases to the atmosphere. Because of the design and the size of the system, internal positive pressure is dangerous to both nearby personnel and equipment. Thus, when pulsating or oscillating pressures occur in the system it must be shut down rapidly to stop the oscillations. For this reason, the periodic instability of the pressure in the system is considered a critical problem. Additionally, the resultant rapid decrease in temperature during an emergency shutdown damages the refractory linings of the kiln and gas purifier.

During the facility shakedown, dramatic pressure oscillations were experienced with spectacular exhibitions of flame from the many ports and seals. A separate study of the pressure oscillations was instituted by Monsanto and the City to discover the origin of the oscillations. Results of the study are considered proprietary by Monsanto, but several pressure transducer data traces were supplied for this study. Figure 20 is a data trace of a sinusoidal pressure pulsation in the kiln.

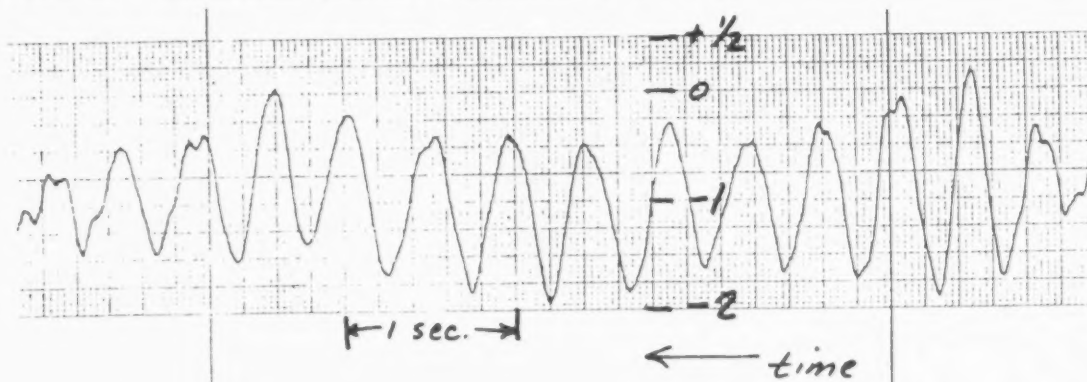


Figure 20. Data trace of sinusoidal pressure pulsation in the kiln.

Random frequency pressure oscillations of low magnitude (Figures 21 and 22 are of such high frequency as to be uncontrollable in a system having the internal volume of the Baltimore plant. At the same time it might be noticed that the magnitude is of little concern other than to indicate basic instability or at least neutral stability. Figure 23 is typical of the pressure oscillations which could be considered dangerous. The steep pressure

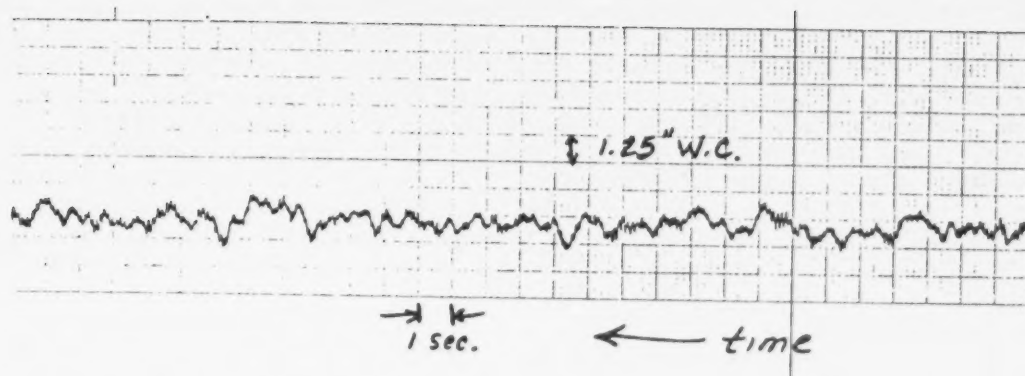


Figure 21. Data trace of random frequency pressure oscillations.

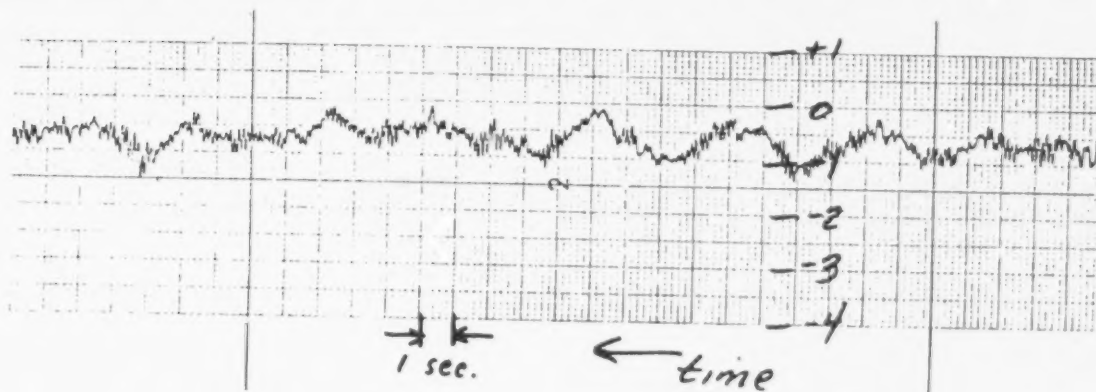


Figure 22. Data trace of random frequency pressure oscillations.

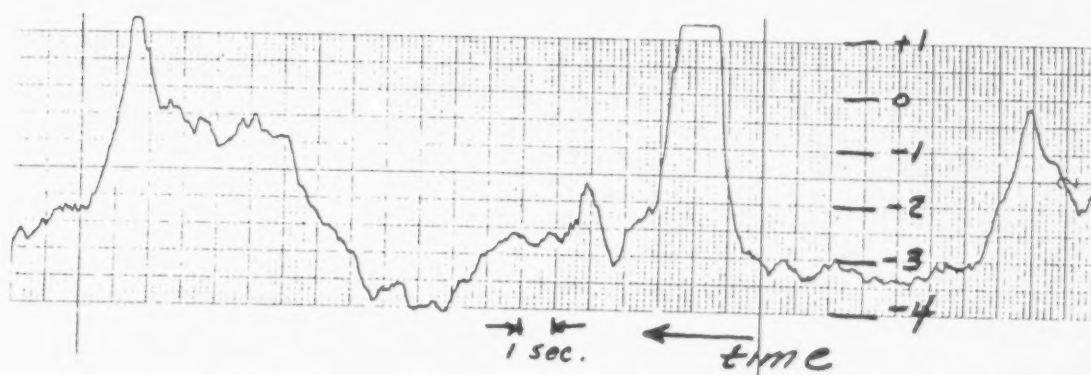


Figure 23. Data trace of dangerous pressure oscillations.

ramps indicate that control of this phenomena after the fact is unlikely and the only cure is to remove the source. The data also indicate that the kiln is probably not acting as an organ pipe resonator. Calculations of the kiln-feed/fire hood configuration indicate a resonant Helmholtz cavity frequency of approximately 5 Hz. The resonance frequency of the pressure traces appears to be approximately 2.2 Hz. The Helmholtz resonant frequency is a very rough approximation since in reality it is difficult to determine what part of the kiln volume might act as part of the resonator volume. Since the volume of the resonator enters the resonant frequency calculation in the form $V^{-1/2}$, the greater the apparent volume, the lower the calculated resonant frequency.

Figure 24 shows traces of pressure at various locations in response to changes in the crossover combustion air and induced draft fan damper positions. These are the only pressure traces available from Monsanto which document pressure response time between the various locations in the system. As can be seen, there is no apparent response delay. The reason for this is the trace speed. Assuming a 425 to 500 mps (1400 to 1600 ft/sec) acoustic velocity, a pressure wave should require only 0.06 to 0.07 sec to pass through the system. The data resolution is not sufficient to accurately identify such time delays.

Monsanto concluded that this type oscillation is not controllable and is related to operation of the oversized crossover combustion air fan which is no longer used.

It has been noted that the crossover combustion air fan was oversized for its task. Typically, centrifugal fans under partial load conditions can develop instabilities. This generally occurs at 1/6 to 1/3 of design volume flow. When a fan discharges into a duct where the volume content is 5 percent or more of the design fan discharge rate, then severe pulsations can occur when the fan is operating at any portion of the characteristic curve where there is a decreasing pressure with decreasing volume flow. This appears to be one cause or source of a forcing function driving a Helmholtz resonator cavity configuration.

At the present time the severe pressure oscillations appear to be under control by not operating the crossover combustion air fan. This problem is not unique to the Landgard process nor is it only typical of refuse processing. It is a problem typical of fan-driven systems and, as such, could occur in any facility where fans are employed.

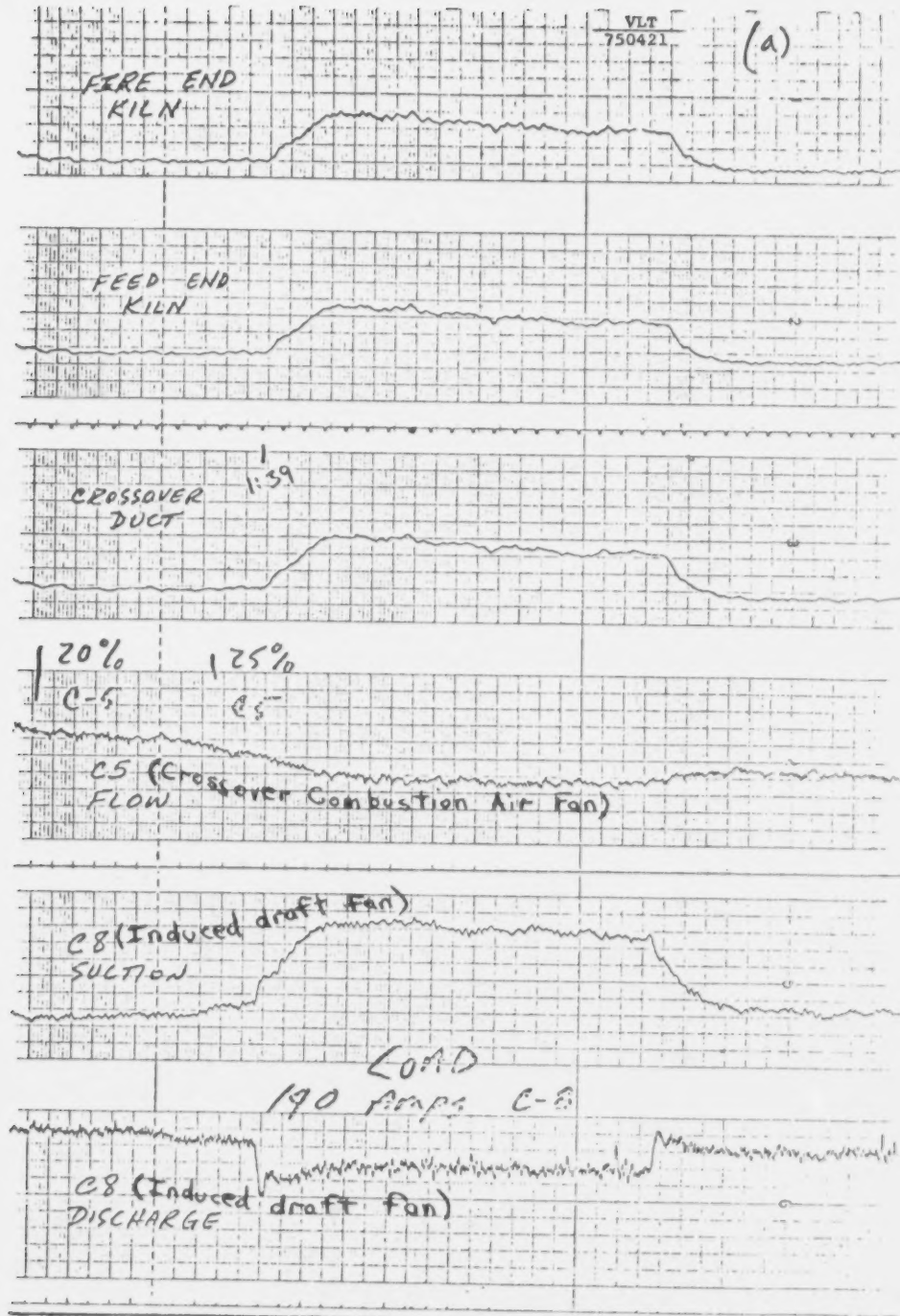


Figure 24. Data traces of pressure at various locations.

SECTION 9

KILN PROCESS CONTROL

Kiln process or temperature control will not directly cause a plant shutdown, but poor process control can cause a range of secondary problems which will precipitate a plant shutdown. High kiln temperatures have caused kiln refractory degradation and kiln slagging with the formation of oversized slag balls which can jam or damage the drag conveyor. Incomplete and unprocessed refuse overloaded the discharge conveyor. Proper processing of refuse in the kiln is probably the most important aspect of reliable operation of the facility.

The thermal processing at the Baltimore plant is actually starved-air incineration rather than true pyrolysis. This process requires that close temperature and combustion air control be maintained to produce a consistently high quality gas product and a trouble-free residue. The original design specified that an O_2/CO_2 analyzer system be used to determine the proper fuel-air ratio and thermocouples to measure temperature. Temperature is an insufficient control parameter to determine proper refuse processing because the peak temperature occurs at the stoichiometric fuel-air ratio. A fuel-air ratio either greater than or less than stoichiometric could result in lower temperature. Hence, knowledge of the fuel-air ratio is also needed to properly control the process.

The pulsating flame front and high temperature combustion zone at the kiln fire/end common at the Baltimore plant were not experienced in the prototype unit. The difference in combustion behavior was reasoned to be the result of differences between the prototype and the Baltimore plant. Numerous calculations and modifications were made and hypothesized to explain the differing behavior. The use of geometric scaling rather than thermodynamic and aerometric scaling is a possible answer since the ratio of gaseous momentum and viscous forces were considerably different between the two systems.

Although turbulence was finally blamed for the aberrant behavior, the reason for the turbulence was not ascertained. In the prototype kiln the refuse combustion air was injected at the kiln centerline and parallel to the axis. In the Baltimore plant the refuse combustion air was injected parallel to the kiln axis but nearly in line with the upper side of the kiln. The result is that recirculation will take place in such a manner that the air will attach to the kiln upper surface through a Coanda effect, spread out over the surface, and force circulation to take place. Numerous solutions were attempted, but the only successful solution was to eliminate the air jet

and distribute the air into the kiln around the kiln perimeter. This modification has minimized the recirculation of the combustion air to eliminate the high temperature fire ball in the discharge end of the kiln. Basically, the problem is one of injection air momentum distribution to prevent local circulation.

Process control requires several phases of measurement and control. First, the residue temperature must be accurately measured. Second, kiln discharge gas must be analyzed for O_2 and CO_2 to determine the fuel-air ratio. Next, the air input flow must be controlled. The present fan inlet louvers control the flow but the actual flow rate is not known. For this reason, each of the fan inlets should be fitted with a simply constructed flow nozzle such as the ISA nozzle for minimum obstruction or clearance requirements. Nozzle differential pressure measurements can, through a simple microprocessor, be used to calculate fan air flow and the resulting calculation used as a feedback signal to an automatic control of the fan louver position. By careful aerodynamic design of the air injection ports, jet diffusion can be accomplished with little or no circulation. The result should be a well-controlled laminar flame front.

This problem must be classified as unique to the Baltimore plant since the prototype facility was not so plagued. Furthermore, the use of a different configuration eliminates the problem.

SECTION 10

O₂/CO₂ ANALYZER SYSTEM

Although no catastrophic failure or shutdown has been directly attributable to a lack of information regarding the oxygen or carbon dioxide levels in the process gas stream, this condition has contributed to a number of system problems. Reliable operation of the O₂/CO₂ analyzers would allow automatic control of the afterburner temperature, minimizing the problem of slag hole pluggage during process disruptions.

Westinghouse instrument technicians indicated that the sampling probe used was a water-cooled probe which employed a water spray to aspirate the probe and moisten the sample. The probe was a premanufactured device selected by Monsanto as meeting specifications and qualifications for application in the Landgard process. Slag particles captured by the probe were supposed to be removed by the spray wash. Three to five micron fly ash (glass slag) particles entered the probe and plugged it about 2 cm (3/4 in.) inside the probe even though provisions were made for back flushing the probes with high velocity air.

In the early demonstration period, good gas samples were obtained from the probes by rodding them on an hourly basis. This practice wasn't within the realm of normal safe operation.

In addition to slag plugging the probe, there was a problem with the water spray which caused flooding of the probe. When excessive water spray was used, it would be drawn back into the sample tube with the gas sample and then into the analyzer where it was frozen by the refrigeration-dehydration system and created a problem in the analyzer. A washer/separator was installed in each probe to attempt to overcome this problem.

City technicians indicated that the standard gases introduced to the analytical equipment for instrument calibration invariably gave good results. Switching to the probe to obtain a gas sample invariably gave no results or unreliable results. In spite of the favorable experience with the calibration gas, the technicians felt that even if a good sample could be brought to the analyzer, the measurement results would be unreliable.

Mislocation of the equipment was blamed by the technicians for all the sampling problems. They indicated that the analyzers were located in a position where oil, grease, and water were constantly dripping or pouring on them and that the analyzer itself was frequently standing in enough water to drown the heaters and cause short circuits or failure of the heating elements

which resulted in the loss of calibration of the equipment. The technicians also indicated that on at least one occasion the prism in the infrared analyzer for CO₂ cracked and had to be replaced, although the exact cause of the problem was not known.

Ultimately, the problem of exposure of this delicate instrumentation to the weather was recognized and plans were made to build an enclosure for the analytical system. A rebuilding effort was undertaken which included replacement of the sample tubes and the installation of sample cleaning water cyclone devices at each probe. Even after this modification no improvement in the analytical capabilities was experienced.

One 10-day experimental trial run was made using a ceramic partial pressure analyzer which was on loan. This device was installed about 25 ft downstream from the gas purifier where a catwalk gave access to the duct. It was reported that the ceramic probe worked well during the 10-day test period. However, after the test probe was returned to the manufacturer, no follow-up was made to assess the appropriateness of this equipment. There are no plans at this time to repair or use the O₂/CO₂ analyzers in the future.

The probe used by Monsanto in the Landgard system at Baltimore is a standard, off-the-shelf item. The sampling probe appears to have been the major cause of failure of the O₂/CO₂ Analysis System since the rodding out of the probes produced good samples.

Westinghouse technicians believed that the probe could have been made operable by installing a shield to screen the probe from the slag in the gas stream and by increasing the vacuum of the probe to overcome the reduced pressure in the sampling position behind the shield. In addition to the slag build-up problem, the probes were also inadequately cooled. This apparently was a two part problem. The first was the lack of assured circulation of cooling water in the probe, and the other was the lack of an indication to assure that the water was turned on. This was especially critical during heat up of the kiln.

The gas samples contained considerable particulate matter. In order to clean the samples of the particulate matter prior to introduction to the analysis system, a cyclone washer was installed at each probe location. While this did reduce the particulate matter in the sample, it also added considerable moisture to the sample stream which, during the winter months, caused condensate and freezing problems in the sample lines. Additionally, it is suspected that both O₂ and CO₂ were absorbed by the water, resulting in a potentially biased analysis. It is not known whether any correction was made for this bias.

The sample handling system that transported gas samples from the probe to the analyzer was not properly designed for the environment in which it was installed. The long lengths of unprotected tubing and numerous tube connections between the probes and the analyzer were subject to abuse, and resulting damage caused leakage of ambient air into the transport tubes.

Insufficient regard was given to the problem of particulate precipitation in the transport tubes which led to blockage of sample gases. Furthermore, the moisture content of sample gases was not adequately considered and freezing of the tubes also occurred. Duplication of the analyzer to service two sampling points did not appear economical at the time of the original design. Events later proved the use of a single analyzer connected to two distant sampling points to be unreliable.

A study of the engineering drawings for the system indicate that the analytical efforts and technologies were well thought out and well engineered. The sophisticated equipment selected appears to be applicable to a controlled environment rather than the outdoor environment in which it was actually installed. The instrumentation is delicate and electrical control circuits are subject to poor performance in ambient weather conditions.

A probe design incorporating the rodding capability would have been appropriate for this application, but a probe design which will create a particle-free wake by ballistic separation at the orifice of the probe may be possible. This would allow extraction of gases from the stream with a low probability of ingesting particulate matter which will clog the probe.

The analytical equipment probably would have operated satisfactorily had it been installed in a temperature and humidity-controlled environment such as inside an office building. However, this being impractical, a housing of its own should have been provided at the outset whereby the instrumentation could have been protected from water, oil, and falling debris.

Another possible solution would be to install a set of the ceramic partial pressure analyzers. The probe for this analyzer is an ion exchange-type and is calibrated to give a measurement of the amount of oxygen in the stream prior to its entrance into the gas purifier. The probe is self contained and needs no gas handling system.

The problems with the analyzer must be considered unique to the Baltimore plant since most of the problems were due to improper installation of the analyzers and improper probe selection.

SECTION 11

INDUCED DRAFT FAN

Since this fan produces the draft through the entire thermal process, the process cannot function when the fan is inoperable. When increasing vibration indicates the necessity for shutdown, an orderly, planned shutdown will minimize the impact on the system. In this case, the penalties are thermal cycling of the refractories with possible thermal shock damage and shortened refractory life, loss of operating time, and increased per ton costs.

An emergency shutdown, due to vibration suddenly exceeding the 0.36 mm (0.014 in.) bearing displacement limit, power failure, or scrubber pump failure has additional penalties. If the kiln stack lid does not open, fire damage can result in the kiln feed area, and hot gases trapped in the system can cause short-term, excessive heating of refractories and equipment. If the kiln stack lid does open, damage to wiring and other equipment can occur from the hot gases escaping the kiln. The rapid cooling results in even greater thermal shocking of the refractories as well as hardening of slag in the kiln and gas purifier in quantities greater than would be the case with an orderly shutdown.

Vibration problems with the induced draft fan started immediately after start-up requiring frequent fan rebalancing. After a few months of operation, the rotor was worn and was replaced with a rotor with wear plates. The vibration and the frequent balancing continued with the new rotor. None of the numerous modifications attempted by Monsanto had any effect. The new rotor was soon worn out even though it had wear plates. The city then decided to operate the plant with the scrubber off. This stopped the corrosion and vibration problems until the scrubber was turned on for steam dumping. The city intends to eliminate the problem by installing a dry ESP system and, consequently, provide for a dry fan.

The gases passing through the fan are heavily loaded with fine particulates and acidic vapors. An analysis of the particulates shows large percentages of alumina and silicon dioxide particles with diameters of a few microns. These particles are highly abrasive and, since steels depend on an oxide layer for corrosion resistance, make the steel components of the fan highly susceptible to corrosion by continually abrading the oxide coating. In addition, since alumina and silica are harder than steel, the particulates probably abrade the steel itself.

When particles are concentrated in a local region, such as the turns where the gas goes through the fan, erosion/abrasion is a potential problem. In an induced-draft fan, blade wear is relatively low at fan-blade-tip speeds under 6700 m/min (22,000 ft/min). Above this tip speed the wear from erosion/abrasion increases very rapidly and higher speeds should not be considered in designs for gases having high concentrations of entrained particles. The rotor of the induced-draft fan, when operated at the design maximum speed of 1200 RPM, has a blade tip speed of 7500 m/min (24,500 ft/min). In order to maintain a tip speed under 6700 m/min (22,000 ft/min) the fan must be operated at less than 1077 RPM. This may necessitate the use of a fan wheel with greater blade width to maintain sufficient draft.

The chlorine content of the gas in conjunction with the moisture in the gas forms an extremely corrosive environment for steels. The presence of chlorine is attested to by the high acidity of the dehumidifier condensate and the analyses of the stack gases. There are also chlorides in the form of HCl in the water droplets and vapor carried over from the scrubber whenever the scrubber liquid swings to the acidic side which occurred periodically due to poor pH control in the scrubber.

The corrosion/erosion problem arises from the use of steel components in an environment for which steel is totally unsuited--a very abrasive and corrosive environment.

The vibration problem is largely one of deposits on the fan rotor aggravated by corrosion/erosion. The spray droplets formed by the scrubber spray nozzles are injected into a relatively hot gas stream. The water in the droplets partially evaporates, thereby raising the solids content of the droplets. Some of the droplets probably become, in essence, sludge droplets. Droplets of this type are carried over the gas stream to the induced-draft fan. Upon striking the surface of the fan blades, these high-solids droplets tend to stick and spread out. The centrifugal forces imparted by the rotating fan would tend to further dewater the solids to form a solid deposit. This condition would be promoted by any pitting of the blade surfaces by corrosion. As the deposit builds up, it becomes susceptible to random flaking due to the impact of large water droplets or centrifugal force. The exposed surface left by the departing flake is subject to corrosion until deposits reform on that area which opens the possibility of uneven corrosion of the metal and uneven build up of deposits with subsequent unbalancing of the wheel.

An analysis of the fan deposits showed a sodium content of 30 percent. Depending on the ratio of NaOH to NaCl, the sodium component content of the deposit would be between 47 and 65 percent. This would verify that the deposits originate in the scrubber water. This analysis and the maintenance history together make a very strong case for the deposits being the major cause of vibration problems.

The problems of abrasion and deposits can both be solved by eliminating the scrubber and substituting a "dry" system for particulate removal such as an ESP or a baghouse. Once the abrasion by particulate matter and erosion of deposits by water droplets have been eliminated, the corrosion problem can be solved by using a fan wheel fabricated of a chlorine-resistant material such as the Hastelloys or some nonmetallic laminate.

Since it appears that the fan problems resulted from the use of the scrubber, the problem must be considered typical of processes using wet scrubbers applied to particle laden gas streams.

SECTION 12

SCRUBBER EROSION AND CORROSION

Failure or shutdown of either of the scrubber pumps would have little impact on system operation since the other pump could continue to operate. Failure or shutdown of both pumps would cause a shutdown of the entire system because of the interlock with the induced-draft fan. Failure of the scrubber lances and nozzles does not necessitate a scrubber shutdown so there would be no impact on system operations other than reducing the spray flow in the scrubber.

SCRUBBER PUMPS

After severe wear, the cast iron scrubber pump impellers were replaced with bronze impellers. The pumps continue to wear and a satisfactory packing to prevent the constant leaking has not been found. The city plans to eliminate this problem by installing a dry ESP unit to replace the scrubber.

When solids fill the bottom of the scrubber to the level of the pump suction pipe, a steady state condition is reached in which all the particulates removed by the scrubber are passed through the pumps with the scrubber water. Monsanto reported that approximately 100 kg/hr (220 lbs/hr) of particulates are going to the scrubber. Even if collection efficiency is low, a large amount of highly abrasive material is passing through these pumps.

Cavitation in the pumps was suspected during operation, and a plate was installed in the scrubber to prevent air from being sucked into the pumps and causing cavitation. However, cavitation can be caused by other factors. If the particulates in the water and the speed of the impeller combine to give the right hydrodynamic conditions, localized cavitation can result from the impact of the particulate against the surface of the impeller.

Cast iron is a very suitable material for pump impellers in an NaOH environment at neutral or basic pH. The suitability of bronze depends upon the particular bronze used and the operating conditions. Control of pH was not very effective and acidic conditions were a common occurrence. During conditions of low pH, corrosion would be severe when combined with the abrasion of the particulates in the water.

The most probable cause of the excessive impeller wear of the scrubber pumps was particulate abrasion aggravated by some cavitation and corrosion.

To solve or at least minimize the impeller wear and to provide good pH control, the scrubber system would have to be redesigned to remove the solids from the scrubber water before they reach the pumps. However, the scrubber is to be replaced with an ESP.

SCRUBBER LANCES AND NOZZLES

The scrubber lances and nozzles have plugged repeatedly and are very difficult to clean. Various types of materials were tested to prevent the corrosion and erosion that occurred to the lances and nozzles. The City intends to solve this problem by installing a dry ESP system and thus eliminate the scrubber system.

The problems with the lances and nozzles can be divided into two areas; internal and external. Internally, the problem is the same abrasion and acid corrosion problem that exists in the pumps except that cavitation is not significant. Abrasion is particularly severe in the nozzles because of the constriction of flow and the sudden change in flow direction. The solution to the problem is the same as for the pumps.

Externally, the problems are caused by the moist acid stream with entrained, highly-abrasive fine particulates. The particulates continually abrade any protective oxide coating on the steel components and the metal itself.

The moist acid vapors are extremely hostile to any steel alloy. This is even worse in the threaded areas of the fittings since threading increases the area for corrosive attack per unit length of pipe and provides sharp ridges and valleys where attack can be concentrated. Where threaded fittings enter threaded connectors, conditions are perfect for crevice corrosion.

When the proper spray patterns are maintained, some measure of protection is provided to the lances from both abrasion and acid attack since the sprays are directed away from them. However, as the nozzles wear, the pattern of the sprays changes and the protection provided by the sprays is gradually diminished. If the excessive erosion/corrosion of the nozzles can be minimized by eliminating the abrasive solids in the scrubber waters and controlling pH, the attack on the external lance surface can be minimized.

Because the excessive wear of the scrubber pumps, lances, and nozzles was caused by improper design of the equipment and materials selection, the scrubber erosion and corrosion problem is unique to the Baltimore plant.

SECTION 13

SUMMARY

While the City of Baltimore has solved many of the problems at the Landgard resource recovery plant by eliminating the source or changing the process configuration, most of the problems could have been solved by equipment modifications.

Refractory failures must be classified as critical since this could result in serious structural damage to the processing vessel or ductwork. After continuous and severe kiln refractory failures, only spalling remains as a problem. The causes of the original kiln refractory failure include: improper installation and curing, exposure to high temperatures, differential expansion between the shell and refractory, thermal shock spalling, and structural spalling. The original kiln refractory failures are therefore unique to the Baltimore plant while the present spalling is unique to the Landgard process. The thickness of the gas purifier refractory has decreased rapidly. This failure was caused by molten slag eroding and dissolving the refractory. This failure is unique to the Baltimore plant since the prototype had a nonslagging afterburner. Refractory failures in the ductwork resulted from the lack of understanding of service condition severity and are considered to be unique to the Landgard process.

Conveyor failure is critical to the operation of the system because of the required continuous flow of materials between the unit processes in the system. Most of the failures with the residue drag conveyor resulted from inadequate knowledge of the process stream characteristics, especially maximum particle size. The kiln residue is typical of the Landgard process, but since a screw conveyor was used in the prototype, the failures are unique to the Baltimore plant. The screw conveyors failed for the same reasons as the residue drag conveyor. These failures are unique to the Baltimore plant because the prototype had a nonslagging afterburner. The storage pit and shredder feed conveyor failures are typical of solid waste processing since the equipment is typical of solid waste handling machinery.

Failure of the ram feeders is a critical problem since the feeders are the mechanisms for advancing refuse into the kiln. The ram feeder failures were of three types: ram jams, snout failure, and hydraulic system failure. The ram jams were caused by snout deformation, the air seal deflection plates, and material overload at the snout entrance. The initial water-cooled snouts failed due to improper manufacturing and operating practice. The present ram snouts failed due to excessive temperature in the kiln. The hydraulic failures resulted from the use of noncompatible equipment. All the ram feeder failures are considered to be unique to the Baltimore plant.

System pressure oscillations are critical because they are hazardous to personnel and equipment. The oscillations were probably caused by the use of the oversized crossover combustion air fan. The problem is unique to the Baltimore plant since it is due to the specific configuration of that system.

Slag hole pluggage is critical because the slag build up in the gas purifier would result in a structural failure of that vessel. Boiler tube slagging is critical because it may cause boiler tube corrosion, low energy recovery efficiency, and possibly an excessive pressure drop through the boilers. Slag hole pluggage occurs because the gas purifier temperature is not maintained at a high enough temperature to ensure proper slag viscosity for slag tapping.

The addition of the quench air ducts prevented molten slag impingement on the boiler tubes but did not prevent a friable slag mass from forming. Since the main heat transfer mechanisms for cooling particulate is radiation, the best solution to cool particulates would be either a slag screen or to cool the duct walls.

Since the slagging gas purifier is unique to the Baltimore plant, the problem of slag hole plugging and boiler tube slagging are also unique to the Baltimore plant.

The failures of the storage and recovery unit are considered critical because they decrease system throughput and increase net processing cost. The failures of this unit include poor refuse retrieval and excessive floor and bucket shoe wear rates. These problems were caused by below design refuse bulk densities, the nature of the refuse (rags, wire, and glass), and the use of inappropriate construction materials. Since only the Landgard process stores primary shredded, mixed municipal solid waste in this type of unit, the failure of this unit is considered typical of the Landgard process.

A failure of the induced draft fan is critical because it must produce the draft through the entire thermal processing system. The fan was frequently shut down due to excess vibration until the system was operated without the wet scrubber. The vibration was probably due to an uneven build-up of solids on the fan impeller and corrosion/erosion of the impeller. Since the fan failures were probably caused by the scrubber, the failures are categorized as unique to the Landgard process.

Failure of the scrubber pumps is not critical unless both pumps fail. The excessive wear of the scrubber pump impeller is probably due to the abrasion caused by the particulates in the recirculating scrubber water, poor pH control of the recirculating scrubber water, and pump cavitation. The excessive wear of the scrubber lances and nozzles was probably caused by particulate abrasion and corrosion. Since the excessive wear of the scrubber was caused by improper design of the equipment and improper material selection, the scrubber problems are considered unique to the Baltimore plant.

Poor kiln process control does not directly cause a plant shutdown but can result in the formation of large slag balls or unprocessed refuse jamming or overloading the residue drag conveyor. The major cause of the poor kiln process control was the inability to monitor the process. Additional control problems were caused by the method of combustion air addition to the kiln in a jet stream which caused recirculation of the gases in the fire end of the kiln. The poor kiln process control is considered unique to the Baltimore plant and has been resolved by system modification.

A shutdown of the residue separation module would not result in a complete plant shutdown. The major cause of operational problems with this module has been poor residue quality. Since the residue separation module is unique to the Baltimore plant, so are its problems. This system has been dismantled and scrapped.

A failure of the O_2/CO_2 analyzer does not directly cause a plant shutdown, but the resulting lack of process control can result in a problem causing a plant shutdown. Most of the analyzer failures resulted from poor probe design and the location of analytical equipment outdoors. Since improper installation and poor probe selection caused the failures, the problem is considered unique to the Baltimore plant.